HIGH-RESOLUTION DIGITAL TERRAIN MODEL FOR THE ITALIAN TERRITORY

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Abstract

High-resolution digital terrain models are essential for environmental planning and territorial analyses, and provide foundations for geomorphological and hydrological applications, including flood and landslide modelling and geo-hydrological hazard and risk assessments. In Italy, airborne LiDAR surveys have improved the representation of terrain morphology in the last decade, but their coverage is heterogeneous, as datasets originate from different local and regional institutions with different acquisition periods. Conversely, the national TINITALY 1.1 model provides a complete coverage at 10 m resolution, though with limited detail in low-relief areas. This study illustrates the HR-DTM-5m, a seamless 5 m-resolution digital terrain model for the entire Italian territory, obtained by integrating LiDAR-derived DTMs with TINITALY 1.1, through a reproducible workflow including harmonisation, regional mosaicking, re-sampling, vertical bias correction and smooth blending of adjacent datasets. The validation procedure was designed to reflect the purpose of the dataset, namely ensuring morphological consistency and hydrological reliability at national scale, rather than maximising point-scale accuracy. Results show negligible vertical bias, smooth transitions across dataset boundaries, improved slope representation in gentle terrains, and better alignment of extracted drainage networks with subtle topographic features. HR-DTM-5m provides a consistent national terrain reference for modelling flood dynamics and slope processes.

Background & Summary

Accurate terrain representation is a fundamental prerequisite for environmental planning, spatial governance, and national-scale territorial analyses. High-resolution digital terrain models (DTMs) provide key information for geomorphological and hydrological analyses, including flood modelling, landslide susceptibility assessment, and the representation of surface processes from local to national scale.

The increasing availability of airborne LiDAR data has significantly improved the level of detail at which terrain morphology can be described, allowing a more realistic representation of slopes, channels, valley floors, and other landform features relevant for geo-hydrological modelling [1].

Despite these advances, the production of high-resolution DTMs with homogeneous national coverage remains challenging, especially in countries where elevation data are collected by multiple institutions following different technical standards. This is the case in Italy, where LiDAR-derived DTMs at 1–2 m resolution are available for large portions of the territory, provided by heterogeneous sources, including regional administrations, national ministries, basin authorities, civil protection agencies, and research institutions. A substantial portion of the available LiDAR data was acquired within the Not-Ordinary Plan of Remote Sensing (NOPRS) promoted by the Ministry of the Environment and Energy Security, which aimed at supporting flood hazard assessment and modelling at national scale. These datasets were acquired at different times, use different coordinate reference systems, and sometimes lack complete or standardised metadata. As a result, LiDAR coverage, although extensive, is spatially fragmented and unevenly distributed across the country [2].

Fig. 1 shows the spatial distribution of LiDAR-derived DTMs across Italy, distinguishing datasets acquired within the NOPRS program from other institutional products.

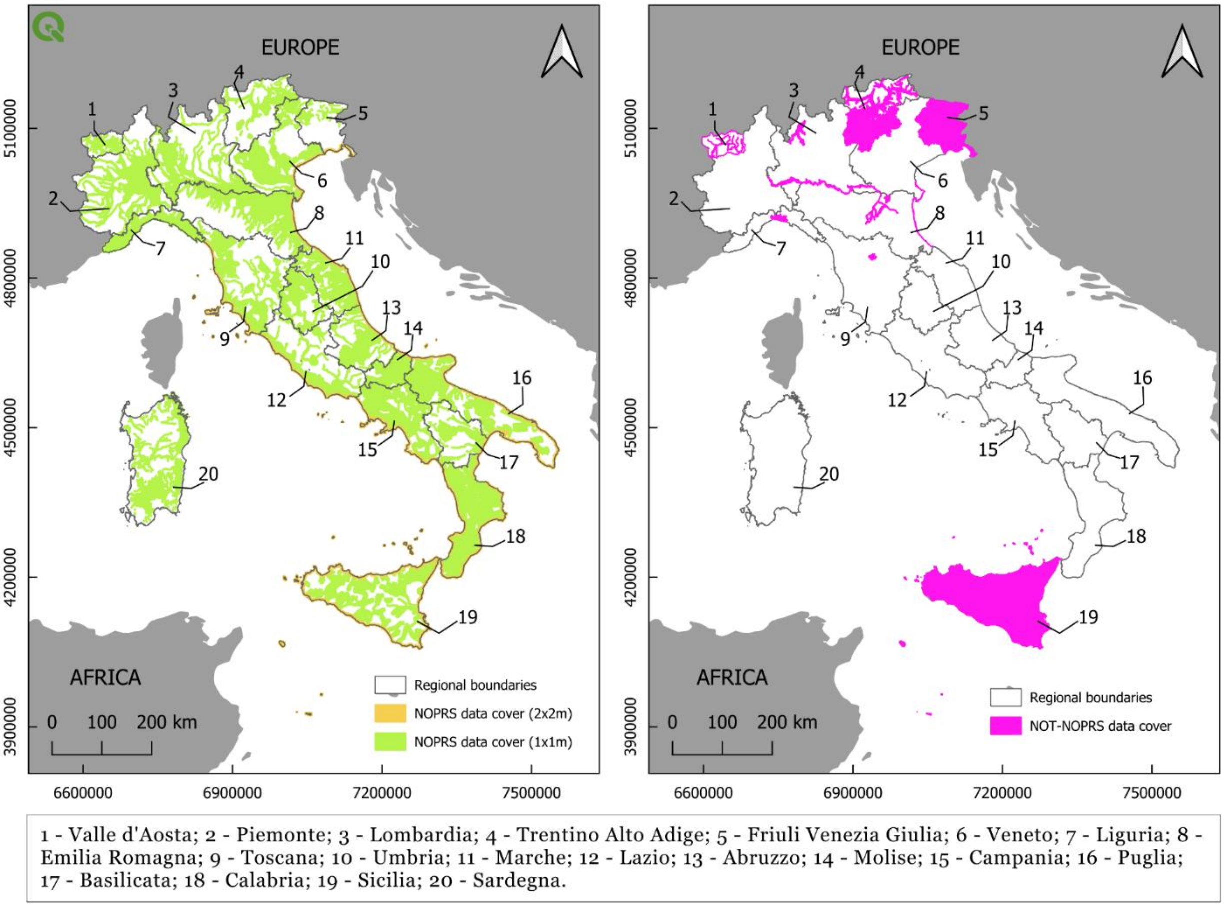

Figure 1: Spatial distribution of LiDAR-derived digital terrain models (DTMs) available in Italy.

In parallel, national-scale elevation models such as TINITALY 1.1 [3–5] available at 10 m-resolution, have played a fundamental role in a wide range of applications, from geomorphology to natural hazard assessment. However, their spatial resolution and underlying data structure impose limitations for modelling workflows that require a detailed representation of terrain features, particularly in low-relief areas. TINITALY 1.1 is derived from a triangulated irregular network, mainly built from contour lines and spot heights. In flat terrain and valley bottoms, where contour density is low and elevation points are sparse, this may result in locally unrealistic flat surfaces that can affect the results of hydrological modelling [6].

Conversely, many LiDAR datasets acquired by the Ministry of the Environment and Energy Security were explicitly designed to support flood hazard modelling. As a result, these surveys preferentially cover valley bottoms and flood-prone areas, often extending upslope along valley sides. This acquisition strategy leads to a strong spatial complementarity between LiDAR-derived DTMs and TINITALY 1.1: LiDAR data are most detailed and reliable where TINITALY 1.1 tends to be less accurate, whereas TINITALY 1.1 generally provides a more consistent representation on steeper hillslopes.

The performance of landslide, rockfall, and rapid flow models [7,8] can be influenced by the resolution and morphological correctness of the input DTM. Similar considerations apply to flood modelling, where the accurate representation of subtle elevation gradients, drainage pathways, and channel–floodplain transitions is essential [9].

Recent literature on DEM fusion and blending has highlighted that integrating elevation datasets characterized by different resolutions and accuracies is a common and necessary practice to achieve spatial continuity and completeness at large scales. A systematic review [10] describes DEM fusion as a workflow composed of pre-processing, fusion, and post-processing steps, and emphasises that different levels of methodological complexity may be adopted depending on the intended application. Within this framework, the blending of adjacent and partially overlapping datasets is widely used to mitigate discontinuities along dataset boundaries and to ensure a coherent terrain surface. Such blending can range from simple weighted averaging across fixed transition zones to more advanced approaches using spatially variable transition widths [1,11,12].

This work illustrates the HR-DTM-5m, a seamless high-resolution digital terrain model for Italy, obtained by integrating LiDAR-derived DTMs and the national TINITALY 1.1 model through a blending approach applied to adjacent and partially overlapping datasets. The dataset is specifically designed to support geomorphological and hydrological modelling and therefore prioritises spatial continuity and morphological realism over the strict optimisation of point-wise elevation accuracy.

Within this context, the HR-DTM-5m dataset integrates many available LiDAR-derived DTMs at 1–2 m resolution through a structured workflow including data harmonisation, regional mosaicking, and blending with the national TINITALY 1.1 model. To ensure consistency, all datasets were harmonised into a common coordinate reference system and re-sampled onto a single grid with a spatial resolution of 5 m.

The choice of a resolution of 5 m represents a deliberate compromise between the very high spatial detail of LiDAR data and the coarser resolution of TINITALY 1.1. This resolution was selected to preserve the essential geomorphological and hydrological information required for national-scale modelling, while maintaining computational feasibility and data manageability. The selected grid spacing is consistent with the spatial scales commonly adopted in flood, landslide, and surface process models, and allows a meaningful representation of terrain features without introducing excessive noise or artificial artefacts, in line with established criteria for selecting an appropriate DEM resolution based on terrain complexity and scale considerations [13].

Blending between adjacent and partially overlapping datasets was systematically performed using smooth transition zones, following established DEM fusion practices [1,11,12]. This approach ensures gradual transitions between areas derived from LiDAR data and areas based on TINITALY 1.1, avoiding sharp elevation steps and other artefacts that could propagate into derived morphometric products and modelling results.

The HR-DTM-5m is conceived as both a scientific dataset and an operational product. The processing workflow is fully automated, reproducible, and scalable, allowing the systematic integration of heterogeneous LiDAR datasets and new acquisitions as they become available, without recomputing the entire national model. By providing a consistent and seamless high-resolution terrain reference, the HR-DTM-5m supports a wide range of geomorphological and hydrological applications and represents a substantial improvement over existing national-scale elevation datasets for Italy.

Methods

The generation of the HR-DTM-5m dataset followed a structured and reproducible workflow designed to integrate heterogeneous elevation datasets into a seamless national digital terrain model. The overall processing chain is summarised in Fig. 2, which provides a schematic overview of the main steps adopted in this work.

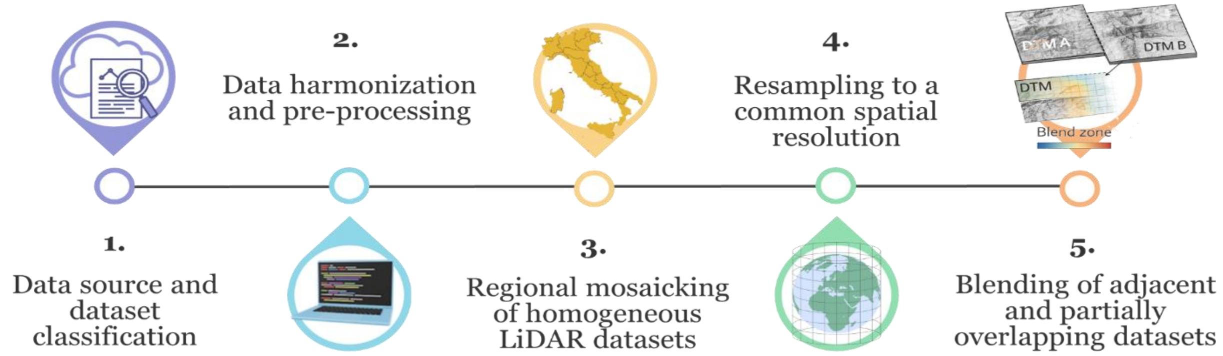

Figure 2: Workflow steps used for the creation of the final HR-DTM model.

The workflow consists of five main steps. First, the input elevation datasets were collected and classified according to their origin and spatial resolution (Step 1). Second, all datasets underwent a harmonisation and pre-processing phase, including re-projection and spatial alignment to a common reference system and grid framework (Step 2). Third, LiDAR-derived DTMs were mosaicked on a regional basis, reflecting their native organisation and administrative distribution (Step 3). Fourth, all elevation datasets were re-sampled to a common spatial resolution of 5 m to enable consistent multi-resolution integration (Step 4). Finally, adjacent and partially overlapping datasets were integrated through a blending procedure, including the correction of systematic elevation offsets between LiDAR-derived DTMs and the national TINITALY 1.1 model, to produce a continuous national-scale terrain surface (Step 5).

The steps of the workflow are described in detail in the following sections, while the quality assessment and validation of the final dataset are addressed separately in the Technical Validation section.

Step 1: Data sources and dataset classification

The HR-DTM-5m dataset was derived from the integration of multiple elevation sources differing in provenance, spatial resolution, coverage, and acquisition period. The main inputs were airborne LiDAR-derived digital terrain models (DTMs) and the national TINITALY 1.1 terrain model.

LiDAR-derived DTMs were obtained from institutional datasets produced by national and local authorities. A substantial portion of the LiDAR data originates from datasets acquired within the Not-Ordinary Plan of Remote Sensing (NOPRS) promoted by the

Ministry of the Environment and Energy Security. Additional LiDAR datasets (NOT-NOPRS), available only for certain Italian Regions, were collected by regional administrations, local authorities and civil protection agencies (see Tab. 1). Overall, LiDAR data are available at spatial resolutions of 0.5, 1, 2 and 5 m and exhibit a heterogeneous spatial distribution across the Italian territory.

The national TINITALY 1.1 model provides complete spatial coverage of Italy at a resolution of 10 m, and represents the reference elevation dataset used in areas where LiDAR-derived DTMs are not available.

Based on their origin and characteristics, elevation datasets were classified into three main groups:

- LiDAR-derived DTMs from national programmes (NOPRS),
- LiDAR-derived DTMs from other institutional sources (NOT-NOPRS), and
- the national TINITALY 1.1 DTM.

This classification was used to organise the processing workflow and to guide subsequent steps of data harmonisation, mosaicking, and blending.

Tab. 1 summarises the main characteristics of the input datasets, including data source, spatial resolution, spatial coverage, acquisition period, and role within the HR-DTM-5m generation workflow. From the table, the non-uniform availability of additional LiDAR datasets (NOT-NOPRS) for the Italian regions can be appreciated.

Table 1: Input datasets.

Dataset Name	Region	Area	Date Start	Date End	Resolution (m)	Link Metadata	Link Viewer	Download	Institution	EPSG
Solar Tirol	Province of Bolzano	Settlement Areas	2013	-	0.5	-	Viewer	Request to Kartografie@provinz.bz.it	Autonomous Province of Bolzano - South Tyrol	32632
LiDAR DTM - Campolongo 2011 - Mosaic 5mx5m	Province of Trento	Costalta-Campolongo high plateau of Pinè	2010	-	5	Metadata	Viewer	Download	Autonomous Province of Trento - Geological Survey	4258
LiDAR DTM - PAT 2006 / 2009	Province of Trento	Provincial coverage	2006	2008	1	Metadata	Viewer	Download	Autonomous Province of Trento - Department of Territory, Environment, Energy and Cooperation - Information Systems Office	4258
DTM 01 PCRFVG	Friuli Venezia Giulia	Regional coverage	2006	2010	1	Metadata	Viewer	Download	Autonomous Region of Friuli Venezia Giulia - Civil Protection	6708
2002-2003 Survey of the Lariano Basin, Lombardy Region	Lombardia	Lariano Basin	2002	2003	2	Metadata	Viewer	Request Form	Lombardia Region	32632
2004-2005 Surveys of the River Po Laser scan	Piemonte/ Lombardia/ Emilia Romagna	Po River	2004	2005	2	Metadata	-	Request Form	Po River Basin Authority	23032
Adda Survey 2014	Lombardia	Adda River	2014	2014	0.5	Metadata	Viewer	Request Form	Research Institute for Geo-hydrological Protection, National Research Council (IRPI-CNR)	32632
Oglio Survey 2014	Lombardia	Oglio River	2014	2014	0.5	Metadata	Viewer	Request Form	Research Institute for Geo-hydrological Protection, National Research Council (IRPI-CNR)	32632
Mera Survey 2014	Lombardia	Mera River	2014	2014	0.5	Metadata	Viewer	Request Form	Research Institute for Geo-hydrological Protection, National Research Council (IRPI-CNR)	32632
DTM APC Reno 2011	Emilia Romagna	Reno River	2011	2011	1	Metadata	Viewer	Download	Bologna Territorial Security and Civil Protection Service	25832
DTM Coast LiDAR 2019	Emilia Romagna	Coastal strip from Chioggia to Pesaro	2019	2019	1	Metadata	Viewer	Download	Emilia-Romagna Region	25832

Dataset Name	Region	Area	Date Start	Date End	Resolution (m)	Link Metadata	Link Viewer	Download	Institution	EPSG
DTM 2022	Emilia Romagna	Municipality of Ferrara	2022	2022	1	Metadata		Download	Municipality of Ferrara	7791
DTM Genova	Liguria	Municipality of Genova	2018	2018	1	Metadata	Viewer	Download	Municipality of Genova	7791
DTM 2023 Firenze	Toscana	Municipality of Firenze	2023	2023	0.5	Metadata		Download	Municipality of Firenze	6707
DTM 2m - ATA 2012 2013	Sicilia	Regional coverage A small portion of the territory (9.17 km²) was discarded due to noticeable elevation errors	2013	2022	2	Metadata	Viewer	Request to area2.sitr@regione.sicilia.it	Sicily Region - Department of Territory and Environment - Interdepartmental Area 2 - Regional S.I.T.R. Node	25833
Not-Ordinary Plan of Remote Sensing (NOPRS)	Italia	Incomplete national coverage	2008	2015	1-2	Metadata	Viewer	Download	Ministry of the Environment and Energy Security	4326/4258
TINITALY 1.1	Italia	National coverage	-	-	10	Metadata	-	Download	National Institute of Geophysics and Volcanology	4326

Step 2: Data harmonisation and pre-processing

Due to the heterogeneous origin of the input elevation datasets, an extensive data harmonisation and pre-processing phase was required prior to their integration. This step aimed to ensure spatial consistency across datasets in terms of coordinate reference systems, spatial alignment, resolution, and data structure, and corresponds to the pre-processing stage of DEM fusion workflows described in Okolie and Smit (2022)[10].

LiDAR-derived DTMs and the TINITALY 1.1 model were originally provided in different formats and coordinate reference systems, including both geographic and projected systems, and, in some cases, different realisations of the same geodetic datum. To manage this heterogeneity, all datasets were first imported into a common processing environment using GRASS GIS, which allowed a structured organisation of data and the application of reproducible geospatial operations, formalized using the bash/GRASS scripting language.

During the initial import phase, datasets were grouped according to their native coordinate reference system. Separate GRASS GIS locations were created for each recognised system, and individual map sets were used to organise datasets, based on their provenance and acquisition characteristics. This approach allowed the preservation of the original spatial properties of each dataset, while enabling controlled and transparent transformations.

All elevation datasets were subsequently re-projected into a common coordinate reference system suitable for nationwide analyses. The adopted target system for the HR-DTM-5m dataset is the national projected reference system EPSG:6875 (Italy zone), which ensures spatial consistency over the entire Italian territory. The re-projection process was performed by explicitly defining spatial extents and grid alignment, in order to avoid the introduction of unintended spatial shifts or re-sampling artefacts.

As part of the harmonisation process, the spatial alignment of all datasets was enforced by referencing a common grid structure. The national TINITALY 1.1 model was used as the reference for defining the spatial extent and grid alignment, ensuring consistency across regions and facilitating subsequent merging operations. This alignment step was particularly important to guarantee that neighbouring datasets could be seamlessly integrated without introducing geometric discontinuities.

At the end of this phase, all LiDAR-derived DTMs and the TINITALY 1.1 model were available within a single coordinate reference system, spatially aligned on a consistent grid framework, and organised in a structured data repository. This harmonised dataset provided the basis for subsequent mosaicking, re-sampling, and blending steps, leading to the generation of the HR-DTM-5m dataset.

LiDAR-derived DTMs are natively distributed and archived on a regional basis by the respective producing institutions; as shown in Fig. 1, this organisation (that reflects Italian administrative boundaries) motivated the adoption of a region-based processing workflow for the subsequent steps.

Step 3: Regional mosaicking of homogeneous LiDAR datasets

After the data harmonisation and re-projection phase, LiDAR-derived DTMs were processed through a regional mosaicking step. This phase aimed to integrate spatially contiguous datasets characterised by homogeneous properties, while preserving internal consistency prior to multi-resolution integration and blending with the national reference model.

Processing was carried out on a regional basis, using Italian administrative regions as the basic operational units, in accordance with the native organisation of the LiDAR datasets. Within each region, LiDAR-derived DTMs were first grouped according to spatial resolution and data source, distinguishing between datasets acquired within the NOPRS programme and those obtained from other institutional sources. This grouping ensured that only datasets with comparable characteristics were merged at this stage.

For each region and for each homogeneous group, individual LiDAR tiles were mosaicked to generate region-wide DTMs. In areas where multiple LiDAR datasets overlapped within the same region, overlaps were resolved by applying a priority criterion exclusively based on data recency, so that the most-recently acquired dataset was retained. This criterion was consistently adopted across all regions.

No smoothing or blending operations were applied during the regional mosaicking phase. The objective of this step was to consolidate datasets with similar spatial resolution and acquisition characteristics, rather than to integrate datasets with different levels of detail or accuracy. As a result, internal terrain features derived from LiDAR data were preserved without modification at this stage.

The output of this phase consists of a set of regionally mosaicked LiDAR DTMs, each characterised by uniform spatial resolution, consistent internal structure, and clearly defined spatial extent. These regional products provided the basis for subsequent re-sampling to a common spatial resolution and for the blending operations applied during the integration of adjacent and partially overlapping datasets.

Step 4: Resampling to a common spatial resolution

Following the regional mosaicking of homogeneous LiDAR datasets, all elevation data were re-sampled to a common spatial resolution in order to enable their integration within a single, seamless national digital terrain model. The adoption of a common grid spacing represents a necessary step in multi-resolution DEM fusion workflows, and allows subsequent blending operations to be applied consistently across datasets.

A target spatial resolution of 5 m was selected as a compromise between the very high resolution of LiDAR-derived DTMs (available at 0.5, 1, 2 and 5 m) and the coarser resolution of the national TINITALY 1.1 model (available at 10 m). This choice was driven by the intended use of the dataset for geomorphological and hydrological modelling at national scale, where an adequate representation of terrain features and spatial continuity is required, while maintaining computational feasibility and manageable data volumes.

Prior to re-sampling, the spatial extent and grid alignment of the target raster were defined consistently with the reference grid adopted during the harmonisation phase. The national TINITALY 1.1 model was re-sampled to 5 m and used as a spatial reference framework for all subsequent operations. The re-sampling was performed through bilinear interpolation, redistributing elevation values from the original 10 m grid onto the finer 5 m grid, without introducing additional topographic information. Regionally mosaicked LiDAR DTMs, originally stored in their native coordinate reference systems and grid definitions, were re-projected to the national reference system and simultaneously aligned to the 5 m target grid. During this transformation, elevation values were re-sampled to 5 m using a bilinear interpolation. This integrated re-projection and re-sampling step ensured exact cell alignment, geometric consistency and numerical compatibility across all datasets prior to the final regional integration.

The re-sampling process was applied uniformly to all regionally mosaicked LiDAR DTMs, regardless of their original resolution. This step ensured that elevation values from different sources could be directly compared and combined during subsequent blending operations, without introducing misalignments or artificial discontinuities at dataset boundaries.

At the end of this phase, all elevation datasets, including regionally mosaicked LiDAR DTMs and the re-sampled TINITALY 1.1 model, were available on a common 5 m grid, spatially aligned and ready for the integration of adjacent and partially overlapping datasets through blending techniques.

Step 5: Blending of adjacent and partially overlapping datasets

After re-sampling all elevation datasets to a common spatial resolution, adjacent and partially overlapping datasets were integrated through a blending procedure designed to ensure spatial continuity and morphological consistency across dataset boundaries. This step corresponds to the fusion stage of DEM integration workflows, as described by Okolie and Smit (2022)[10].

Blending was applied systematically to integrate datasets characterised by different spatial resolutions and data origins, including neighbouring regional LiDAR mosaics and, subsequently, LiDAR-derived DTMs with the national TINITALY 1.1 model. The procedure was designed to minimise boundary discontinuities and ensure terrain coherence for geomorphological and hydrological applications.

Before blending LiDAR-derived DTMs with the TINITALY 1.1 model, a preliminary correction of systematic elevation offsets was applied to the LiDAR datasets. This correction aimed to minimise the mean elevation difference between LiDAR-derived DTMs and TINITALY 1.1 in areas of spatial overlap, bringing the average difference close to zero. The bias was computed after harmonisation, re-projection, and re-sampling at 5 m, and was defined as the mean elevation difference calculated over all the overlapping cells. The correction was applied as a constant vertical offset, preserving internal terrain morphology while ensuring a consistent vertical reference between datasets.

After applying the above correction, a quality control phase was performed to identify and manage extreme values in the dataset. Outliers were detected by combining univariate descriptive statistics with spatial inspection of the geographical distribution of outliers. This check revealed the presence of unusually low elevations in specific areas, attributable to two main issues: (i) in the Veneto region, minimum values of approximately −560 m were identified, attributable to incorrect altitudes affecting a subset of tiles in the NOPRS set; (ii) along the Lariano-Como river section, NOT-NOPRS data included bathymetric/channel information, producing elevations lower than the surrounding land. To eliminate these artefacts, a conditional filter was implemented, setting all cells with elevations below −5 m a.s.l. to “NoData”. The threshold of −5 m was selected by considering that the lowest emerged altitudes documented in the Po River delta (Northern Italy) refer to widespread land subsidence caused by historical deviations in the river course, hydraulic engineering works, groundwater/gas extraction, reduced sediment supply, and embankment confinement, that lowered vast areas to approximately −5 m a.s.l.[14].

In a localised area, elevations below this threshold correspond to a real topographical depression. This sector is an open-pit quarry with a minimum elevation of −46.3 m: this value therefore represents the actual minimum elevation of the final DTM on a national scale. Accordingly, the original LiDAR elevations were retained in this area, whereas the < −5 m filter was applied to the remaining anomalous cells.

Following this adjustment, blending between the LiDAR-derived DTMs and the re-sampled TINITALY 1.1 model was performed using smooth transition zones. The blending approach adopted in this work follows established DEM fusion practices based on gradual transitions between adjacent datasets[1,11,12]. Within these transition zones, elevation values from overlapping datasets were progressively combined, allowing smooth changes in elevation and slope across boundaries.

Priority was consistently given to LiDAR-derived DTMs over the TINITALY 1.1 model in areas of spatial overlap, reflecting the higher spatial resolution and more detailed representation of terrain features provided by LiDAR data.

The blending procedure was applied iteratively across the study area, first within regional boundaries and subsequently across region borders, until a fully continuous national-scale terrain surface was obtained. This stepwise integration allowed the management of local overlaps while ensuring overall spatial coherence at the national scale.

The resulting blended surface reflects a balance between retaining high-resolution terrain features and ensuring spatial continuity across datasets. In line with the intended use of the HR-DTM-5m dataset, the blending procedure favoured morphological consistency and smooth transitions rather than the strict optimisation of point-wise elevation accuracy, allowing unbiased and reliable estimations of geomorphometry.

Data Record

The dataset is organized as a single georeferenced raster file, hosted in the Zenodo repository at the following URL: https://zenodo.org/records/18921767[1]. The dataset consists primarily of a single GeoTIFF file and has dimensions of approximately 195,520 pixels in width and 257,218 pixels in height, with data stored as 32-bit floating-point values representing elevation. The GeoTIFF is compressed using the DEFLATE method and uses band interleaving. The spatial reference system is RDN2008 / Italy zone (EPSG:6875), with a Transverse Mercator projection and specific projection parameters detailed in the accompanying metadata. The data are georeferenced with the upper-left corner at metric coordinates (6577720, 5209660) and a pixel size of 5 metres in both directions, with the axes aligned with the TINITALY 1.1 model.

Technical Validation

The validation of the HR-DTM-5m dataset was designed to assess the internal consistency, spatial continuity, and morphological reliability of the final terrain surface, with specific reference to its intended use for geomorphological and hydrological analyses.

Given the heterogeneous nature of the input datasets and the adopted integration strategy, the validation did not aim at maximising point-wise altimetric accuracy, but rather at verifying that the resulting model provided a coherent and functionally reliable representation of terrain morphology across the whole Italian territory.

The quality control phase was carried out to identify residual artefacts, elevation discontinuities, or internal inconsistencies that may had been introduced during the harmonisation, re-sampling, and blending stages. Such assessment was conducted using GIS-based analysis and GRASS GIS geomorphometric tools commonly adopted for terrain analysis, including slope computation, shaded relief generation, and profile extraction[15–17]. To this purpose, a few validation tests were performed in different areas of the national territory.

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[1] The associated manuscript has been submitted to a scientific journal and is currently under review. During the scientific journal review period, the product is available from the authors upon request.

Morphological continuity and profile analysis

A key component of validation is the analysis of topographical profiles extracted from representative geomorphological settings, including valley bottoms, gentle slopes, and areas characterised by transitions between the LiDAR-derived DTMs and the national TINITALY 1.1 model. Selected profiles (Fig. 3) allowed for a direct comparison between TINITALY 1.1, NOPRS, and the final HR-DTM-5m surface.

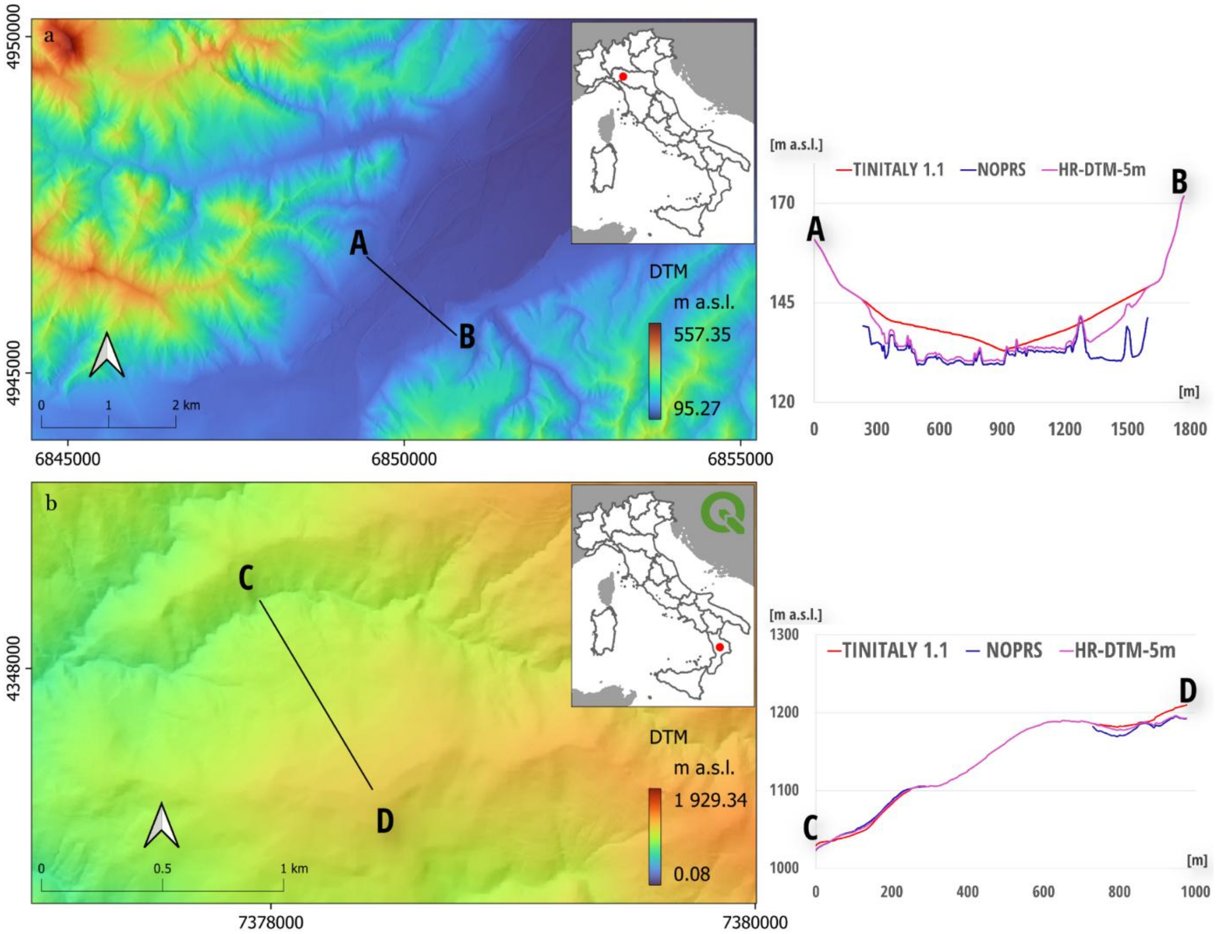


Figure 3: DTM of a floodplain/river-channel sector (Emilia-Romagna, Northern Italy, shown in Fig. 1) with the profile trace, and elevation profiles extracted along the same transect from TINITALY 1.1, NOPRS, and the final HR-DTM-5m surface. Colours in the legend identify the corresponding dataset (a). DTM of a high-relief mountain setting in Calabria, Southern Italy (shown in Fig. 1) with the profile trace, and elevation profiles extracted along the same transect from TINITALY 1.1, NOPRS, and the final HR-DTM-5m surface. Colours in the legend identify the corresponding dataset (b).

The profiles show that, in areas not covered by LiDAR data, the HR-DTM-5m preserves the elevation trends of TINITALY 1.1, ensuring consistency with the national reference model. Conversely, where LiDAR data are available, the HR-DTM-5m follows the higher-resolution terrain information, capturing subtle elevation variations that are not resolved in the coarser model. In transition zones, the applied blending procedure produces smooth and gradual changes between datasets, avoiding abrupt elevation steps or artificial break lines. This behaviour confirms the effectiveness of the adopted fusion strategy in ensuring spatial continuity while preserving local terrain detail.

To assess the geomorphological consistency of the product, a morphological classification was performed using the r.geomorphon tool[18] implemented in GRASS GIS. The analysis was applied to the TINITALY 1.1 and the HR-DTM-5m, using the same parameter configurations (search = 5), to assess the degree to which enhanced spatial resolution improves terrain representation (Fig. 4).

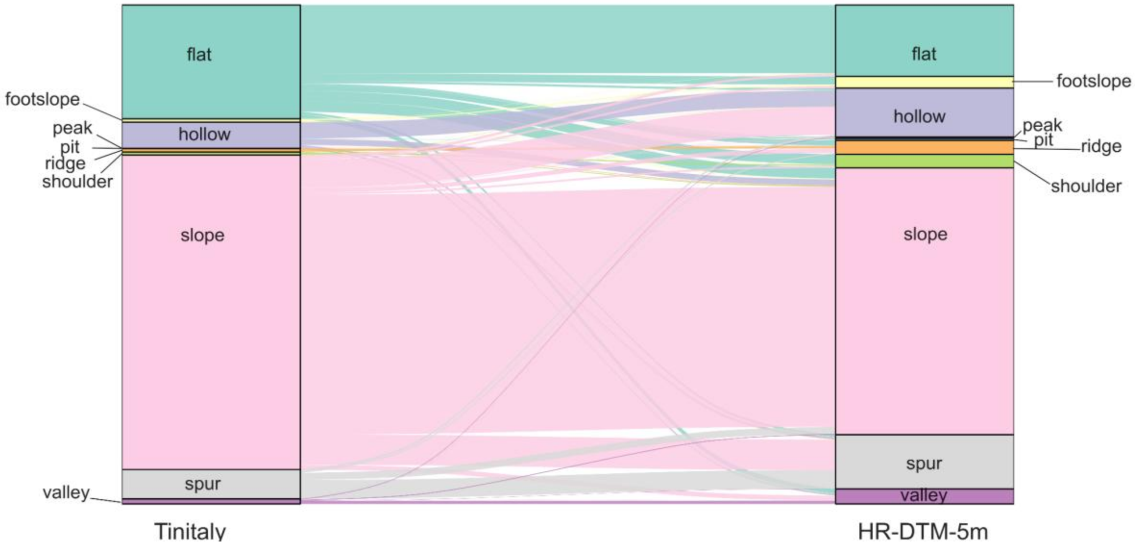


Figure 4: Sankey diagram of geomorphic class transitions between TINITALY 1.1 and the final HR-DTM-5m, showing reduced flat and slope classes and improved delineation of specific landforms in the HR-DTM-5m.

The results demonstrate a more refined and spatially differentiated delineation of landform elements in the HR-DTM-5m, accompanied by a substantial reduction in the areal extent of generic slope and flat classifications compared to TINITALY 1.1. This finding suggests that the HR-DTM-5m mitigated terrain generalisation by enabling the reclassification of areas, previously characterised as flat or uniformly-sloping in coarser-resolution models, into more specific, geomorphologically diagnostic categories (e.g., hollow, footslope, ridge, shoulder, spur, and valley). Such redistribution of landform classes reflects the enhanced capacity of the HR-DTM-5m to resolve fine-scale topographic variations and to yield a more robust representation of terrain morphology.

Elevation: statistics

The analysis of altimetric statistics was extended to the national scale to compare the hypsometric distribution of HR-DTM-5m to that of TINITALY 1.1 (re-sampled at 5 m), to verify the overall consistency of the two products and to identify any systematic deviations. Table 2 summarises the statistics obtained. The two DTMs show almost identical coverage (12,004,375,366 valid cells for HR-DTM-5m and 11,993,718,740 for TINITALY 1.1), with a difference of 10,656,626 cells (~0.089%), mainly attributable to edge effects and NoData management.

Table 2: Summary of altimetric statistics for HR-DTM-5m and TINITALY 1.1 (re-sampled at 5 m) at national scale (whole Italian territory). Elevation values are expressed in metres (m).

Metrics	HR-DTM -5M	Tinitaly 1.1
Minimum	-46.3	-49.3
Maximum	4805.9	4806.5
Range	4810.9	4852.8
Mean	535.5	535.9
Standard deviation	586.2	586.1
Variation coefficient	109.5 %	109.4 %

The overall statistics are very similar (average elevation: 535.5 m vs 535.9 m; standard deviation: 586.2 m vs 586.1 m), supporting the vertical consistency between the two datasets. The minimum and the maximum are essentially the same (-46.3 m vs. -49.3 and 4805.9 m vs. 4806.5 m).

To statistically describe the altitude deviations, the difference

$$\Delta z = \text{'zTINITALY'} - \text{'zHR-DTM-5m'}$$

and the percentiles (cf. Table 3) were analysed. The distribution is centred around 0 m (P50 = 0 m): the positive values reach P95 = 5.9 m and P99 = 16.7 m, whereas the negative tail reaches P5 = −15.1 m (P10 = −5.2 m; P25 = −2.8 m).

Table 3: Descriptive statistics for the elevation difference between TINITALY 1.1 (5 m) and HR-DTM-5m. Values are expressed in metres (m).

Metrics	**Value**
Minimum	-113.8
P5	-15.1
P10	-5.2
Q1 (P25)	-2.8
Median (P50)	0.0
Q3 (P75)	0.4
P90	3.2
P95	5.9
P99	16.7
Maximum	201.6
Mean	0.1
Standard deviation	5.0

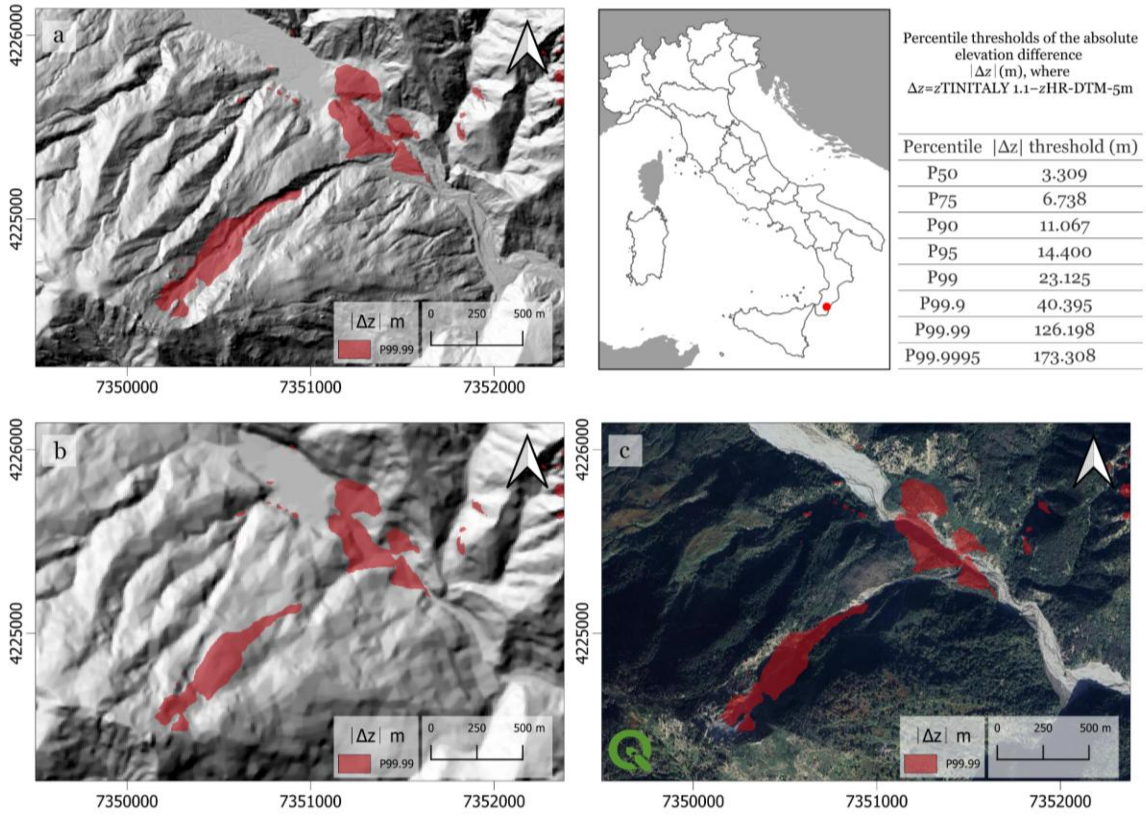
The map of the absolute value of the differences ($|\Delta z|$) was used to identify the most significant elevation differences (Figs. 5-6).

On a national scale, the greatest deviations are mainly concentrated on very steep slopes and areas with high curvature, where a lower resolution of TINITALY 1.1 tends to smooth out the morphology and may not be able to represent narrow incisions, gullies, and topographic details (that are better resolved by HR-DTM-5m).

Some of the outliers may also be associated to evidence of geomorphological processes and/or to anthropogenic changes to the surface (e.g., landslide scarps and deposits; quarries and accumulations of fill material). The Calabrian examples shown in Figs. 5–6 are reported as representative cases to exemplify the geomorphological interpretation of such anomalies.

In particular, Fig. 5 provides an example of a landslide setting, whereas Fig. 6 concerns a quarry area. Note that the quarry was not active at the time of acquisition of the elevation information used for TINITALY 1.1, and resulted to be excavated when LiDAR data were acquired. Such anthropogenic modification of the slope explains the observed local maximum discrepancy (160 m).

In Figs. 5-6, the percentile-threshold tables are reported to facilitate the interpretation of the mapped classes.

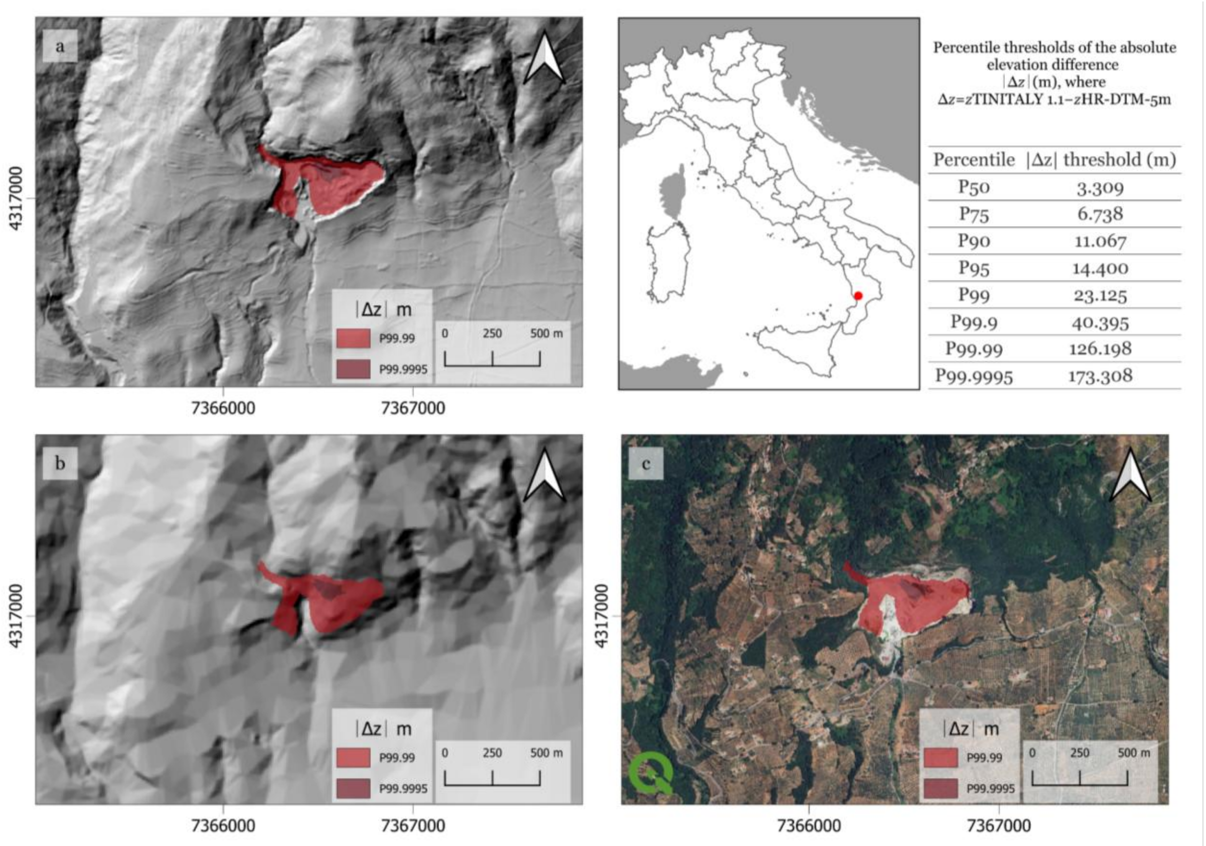


Percentile thresholds of the absolute elevation difference |Δz| (m), where Δz=zTINITALY 1.1−zHR-DTM-5m

Percentile	|Δz| threshold (m)
P50	3.309
P75	6.738
P90	11.067
P95	14.400
P99	23.125
P99.9	40.395
P99.99	126.198
P99.9995	173.308

Figure 5: Sample area of Calabria affected by gravitational phenomena. Areas having values larger than 99.99 percentile of the |Δz| maps are superimposed on: (a) the hillshade derived from HR-DTM-5m, (b)

the hillshade derived from TINITALY 1.1, (c) a satellite image (Google, Imagery @2006 Airbus). The table shows the percentile thresholds used for the classification of |Δ*z*|.



Percentile thresholds of the absolute elevation difference |Δ*z*| (m), where Δ*z*=*z*TINITALY 1.1−*z*HR-DTM-5m

Percentile	|Δz| threshold (m)
P50	3.309
P75	6.738
P90	11.067
P95	14.400
P99	23.125
P99.9	40.395
P99.99	126.198
P99.9995	173.308

Figure 6: Sample area of Calabria affected by mining activities (quarry). Areas having values larger than 99.99 and 99.9995 percentiles of the |Δz| maps are superimposed on: (a) the hillshade derived from HR-DTM-5m, (b) the hillshade derived from TINITALY 1.1, (c) a satellite image (Google, Imagery @2006 Airbus). The table shows the percentile thresholds used for the classification of |Δ*z*|.

Slope representation and terrain gradients

For the slope-based validation phase, a 146.33 km² sample area in Piemonte was considered. Slope maps derived from HR-DTM-5m (Figs. 7-a) and from TINITALY 1.1 re-sampled at 5 m resolution (Fig. 7-b) were compared to assess how different terrain representations affect slope patterns and the areal distribution of slope classes.

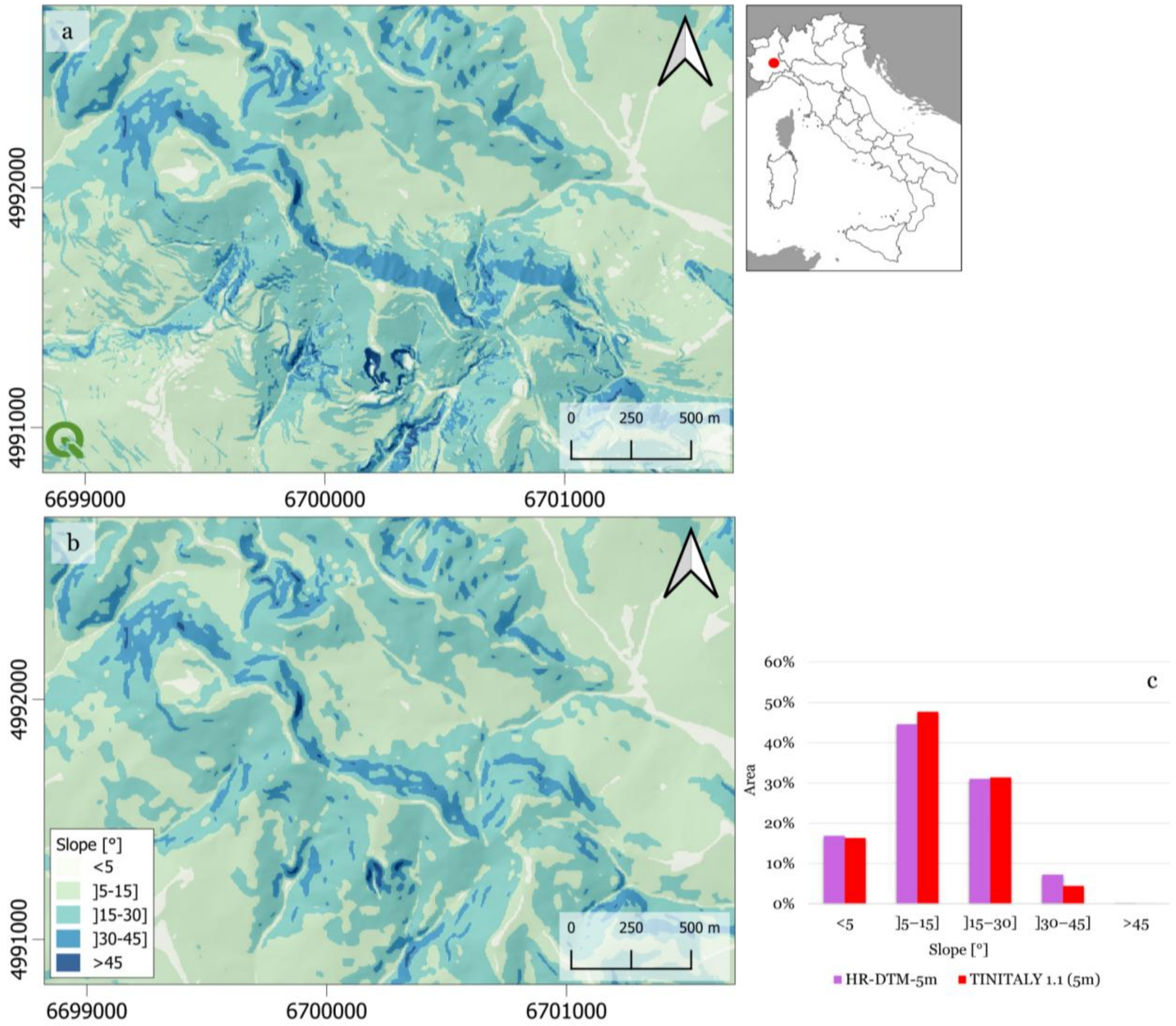


Figure 7: Slope maps (degrees) for the Piemonte test area derived from HR-DTM-5m (a) TINITALY 1.1 (b) and slope class distribution comparison (HR-DTM-5m vs TINITALY-5m) (c).

As shown in Figs. 7-c, TINITALY 1.1 has a higher percentage of gentle slopes (5-15°), in line with a more smoothed surface area, whereas HR-DTM-5m shows a higher percentage of steeper slopes (30-45°), reflecting its greater ability to capture small-scale incisions, slopes and local slope transitions.

Hydrological coherence

Hydrological coherence was investigated by extracting flow direction and drainage networks, using the GRASS GIS r.watershed algorithm[19,20], and comparing networks derived from TINITALY 1.1 and HR-DTM-5m. Results show improved recognition and alignment of flow pathways in HR-DTM-5m, especially in low-relief and floodplain contexts, while preserving TINITALY-derived drainage geometry in areas where HR-DTM-5m relies on the re-sampled national model (Fig. 8).

Fig. 8a further illustrates the behaviour of the extracted networks across areas characterised by different data sources. Where the HR-DTM-5m relies exclusively on the re-sampled TINITALY 1.1 model, the drainage networks derived from the two datasets are nearly identical, confirming that the integration procedure preserves the geometry of the national reference model in the absence of LiDAR data. Conversely, in areas covered by LiDAR surveys, the HR-DTM-5m captures additional terrain detail, resulting in a more articulated and morphologically consistent river network, with improved representation of channel curvature and local flow convergence.

In Fig. 8b, the river network extracted from the HR-DTM-5m (green) is compared with the network derived from TINITALY 1.1 alone (blue), over a shaded relief computed from the HR-DTM-5m. The HR-DTM-5m allows a more accurate alignment of drainage paths with subtle morphological features, such as shallow incisions, channel margins, and gently sloping valley floors, which are poorly resolved in the coarser national model. This improvement is especially evident in flat areas, where small elevation gradients control flow routing and where the TINITALY-based network tends to oversimplify or misplace drainage paths.

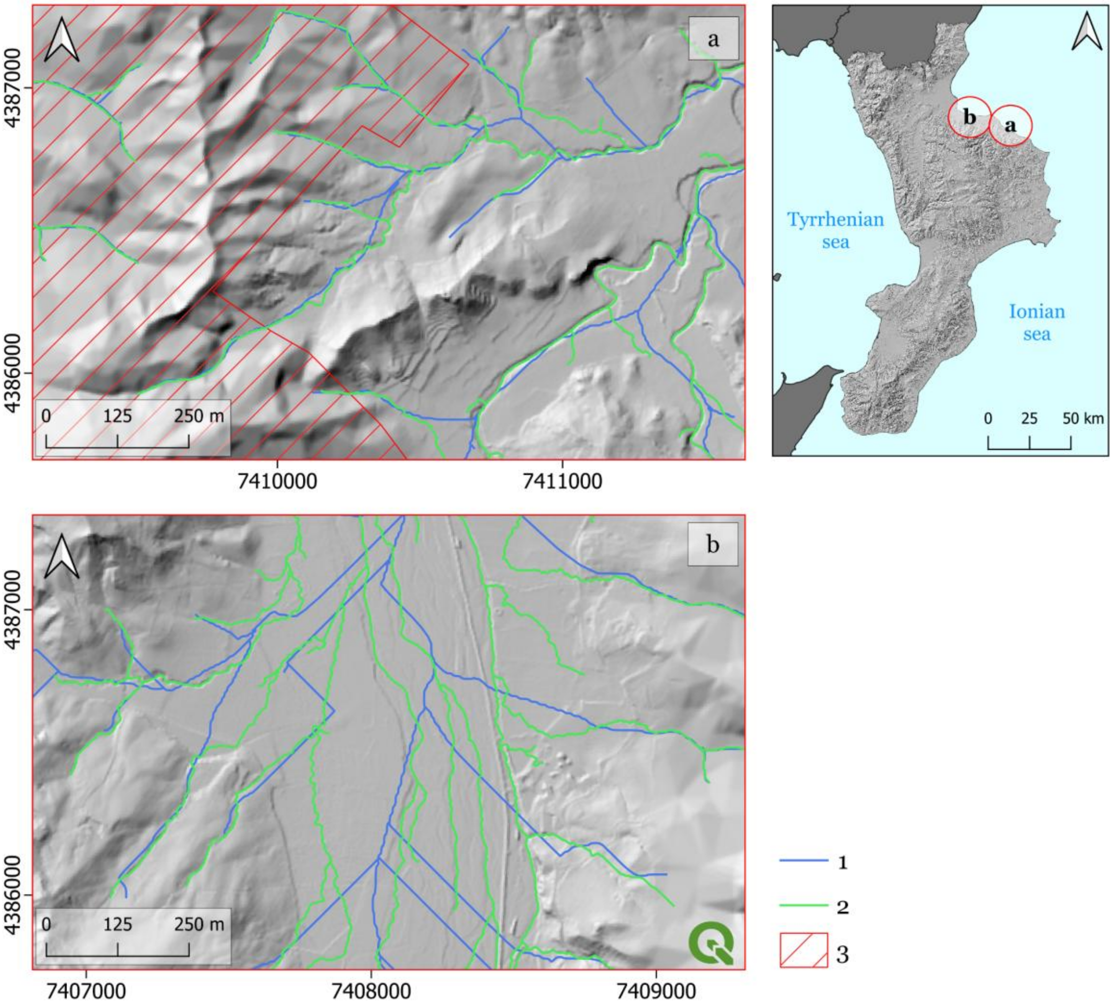


Figure 8: Drainage networks extracted with GRASS GIS r.watershed [19,20] from TINITALY 1.1 (1, blue) and HR-DTM-5m (2, green), over a hillshade derived from HR-DTM-5m. Hatched polygon (3) delineates the area covered only by TINITALY 1.1.

Visual assessment and shaded relief analysis

Shaded relief maps (Fig. 9) were used as an additional qualitative validation tool to assess the morphological realism of the HR-DTM-5m. The hillshade representation highlights terrain features (e.g., channel margins, meanders, terraced slopes) more clearly than the national reference model, particularly in low-relief environments.

The visual comparison in Fig. 9a,b confirms that the HR-DTM-5m does not introduce spurious artefacts at dataset boundaries and provides a spatially coherent representation of terrain morphology across areas derived from different data sources.

A further example in a landslide-prone sector is shown in Fig. 9c,d.

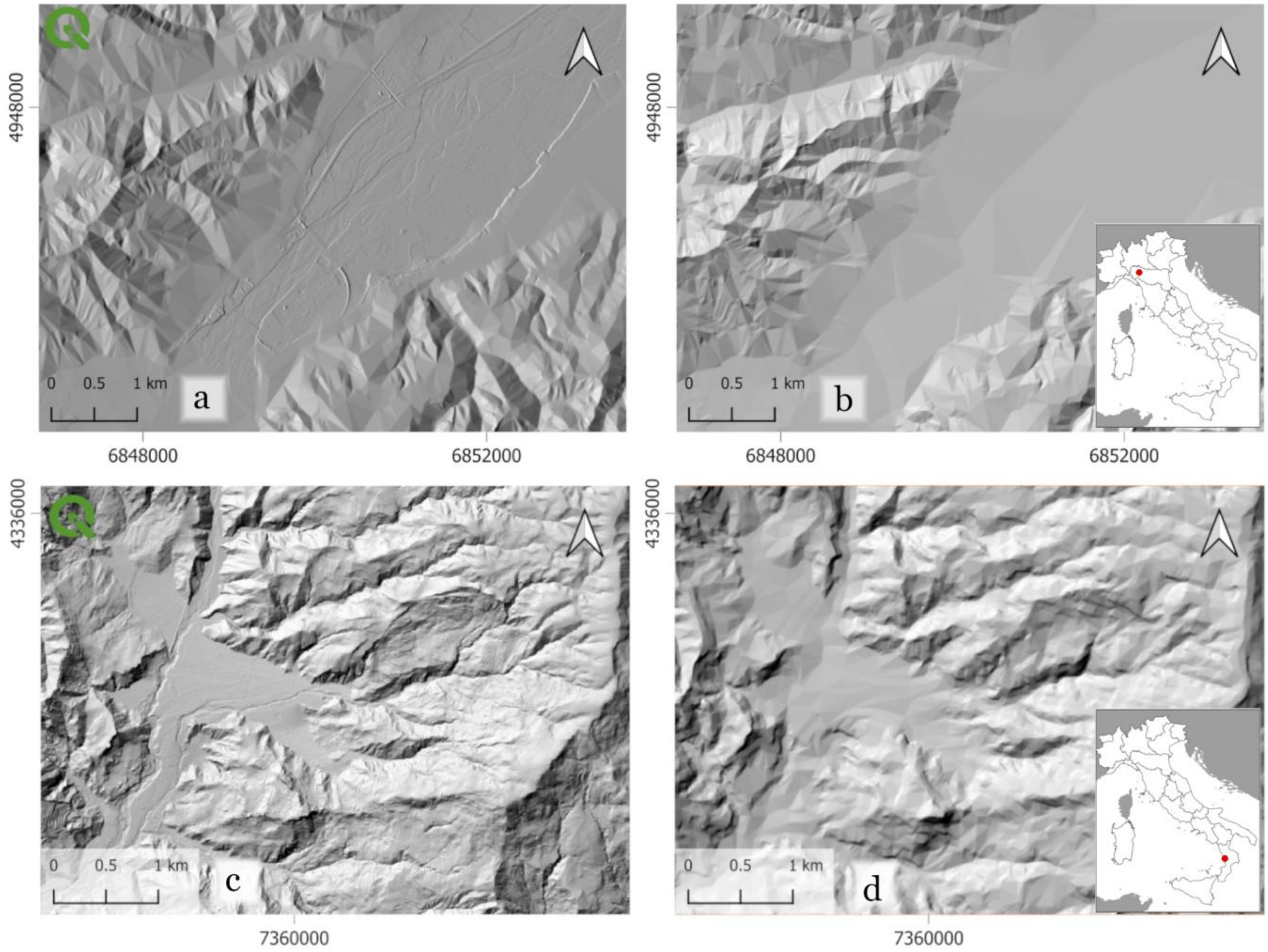


Figure 9: Comparison between the hillshade (relief) derived from the HR-DTM-5m (a-c) and TINITALY 1.1 (b-d) in representative areas of a floodplain (Emilia-Romagna), showing the differences in geomorphological characteristics (a-b) and in an area characterized by high slope instability (Calabria) (c-d).

Data Availability

The dataset is hosted in the Zenodo repository at the following URL: https://zenodo.org/records/18921767[2]. It is provided as a single georeferenced raster file in GeoTIFF format. The file contains elevation data stored as 32-bit floating-point values and is compressed using the DEFLATE method.

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[2] The associated manuscript has been submitted to a scientific journal and is currently under review. During the scientific journal review period, the product is available from the authors upon request.

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Author contributions

MM played a central role in the technical development of the dataset, contributing to software implementation, validation activities, formal analyses, investigation and data curation. She was also responsible for preparing the original draft of the manuscript and for the visualization of the results. MP contributed to the software development and to the analytical components of the work, including formal analysis and investigation, and supported resource collection and data curation. He also contributed to drafting the manuscript.

MR contributed to the conceptual and methodological development of the study and provided scientific supervision throughout the research process. He also contributed to the critical review and editing of the manuscript and was responsible for funding acquisition. MA participated in the conceptualization and methodological definition of the work, provided supervision, and contributed to the review and editing of the manuscript. GI provided supervision and contributed to the review and editing of the manuscript, as well as to funding acquisition.

IM led the conceptual development and methodological design of the study. He contributed to software development, validation and formal analysis, provided resources, prepared the original draft, supervised the research activities, coordinated project administration, and was responsible for funding acquisition.