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Multi-strata geomorphological database (MorphDB): a methodological breakthrough in geomorphological mapping approach

Abstract: Bosino A., La Licata M., Franceschi L., Hafiz A., Maggi V., Maerker M., Szatten D., De Amicis M., *Multi-strata geomorphological database (MorphDB): a methodological breakthrough in geomorphological mapping approach.* (IT ISSN 0391-9838, 2024). From the beginning of the past century geomorphological maps have been generated through detailed field surveys representing Earth surface landforms and deposits fixed on sheets of printed paper. The introduction of Geographic Information Systems (GIS) in the last decades has allowed the addition of more information to each mapped landform through the construction of specific geodatabases. However, the prerequisite to compile a detailed map is the detection of the landforms with the highest degree of accuracy without losing information and respecting the geomorphological criteria and cartographic rules. In fact, arbitral hierarchy between landforms (i.e., order of overlapping landforms) as well as the derived topological issues can significantly affect the represented geomorphological information in the map. We propose here an innovative GIS-based methodology to overcome the above-mentioned issues, introducing a multi-strata geomorphological database (MorphDB). This approach offers the possibility to map each landform with high spatial and temporal detail by implementing geomorphological information, and other morphometric evidence into a structured and searchable geodatabase. The proposed methodology was tested in a portion of the upper Arda Valley (Northern Apennines, Italy) compiling the geodatabase and assembling a geomorphological map. Finally, the MorphDB was shared in a GeoPackage file (.gpkg) in order to allow its use in other in other morphogenetic contexts. This study will open a new perspective in geomorphological mapping, contributing to reduce cartographic errors, loss of information due to generalization processes and the production of derived maps exploitable for territorial planning.

Key words: geomorphological mapping, geodatabase, GIS, applied geomorphology.

Riassunto: Bosino A., La Licata M., Franceschi L., Hafiz A., Maggi V., Maerker M., Szatten D., De Amicis M., *Database geomorfologico a multistrati (MorphDB): una svolta metodologica nell'approccio della cartografia geomorfologica.* (IT ISSN 0391-9838, 2024). Dall'inizio del secolo scorso le carte geomorfologiche sono state realizzate attraverso indagini dettagliate sul campo al fine di rappresentare le forme e i depositi di diversa genesi della superficie terrestre fissandole su un foglio di carta stampato. Solo negli ultimi decenni l'introduzione dei Sistemi Informativi Geografici (GIS) ha contribuito ad aggiungere un maggior numero di informazioni a ciascuna forma rappresentata attraverso la costruzione di geodatabase specifici. Tuttavia, il prerequisito per realizzare una carta dettagliata è l'individuazione delle forme del rilievo con il più alto grado di particolare possibile, senza perdere informazioni e rispettando i criteri del rilevamento geomorfologico e della rappresentazione cartografica. Infatti, sia l'arbitraria gerarchia di rappresentazione tra forme (ovvero l'ordine di sovrapposizione delle stesse) sia i problemi topologici che ne derivano possono influenzare significativamente le informazioni geomorfologiche rappresentate nella carta. La metodologia qui proposta è innovativa, basata su tecniche GIS, e consente di superare i problemi sopra menzionati, introducendo un database geomorfologico multi-strato (MorphDB) che permetterà di cartografare ogni porzione di territorio con grande dettaglio spaziale. In questo modo le informazioni geomorfologiche e le altre informazioni morfometriche potranno essere assemblate in un geodatabase strutturato. La metodologia è stata sperimentata in una porzione dell'alta Val d'Arda (Appennino settentrionale, Italia) implementando il geodatabase e assemblando una carta geomorfologica. Infine, il MorphDB è stato condiviso in formato GeoPakage (.gpkg) per poter essere adottato in differenti contesti morfogenetici. Questo studio aprirà nuove prospettive nella cartografia geomorfologica, contribuendo ad attenuare errori di rappresentazione, perdita di informazioni nelle aree di sovrapposizione di forme con conseguente produzione di carte derivate utilizzabili ai fini della pianificazione territoriale.

Termini chiave: cartografia geomorfologica, geodatabase, GIS, geomorfologia applicata.

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INTRODUCTION

Geomorphological maps are fundamental tools to understand Earth surface processes and landforms, natural resources, natural hazards, and landscape evolution aspects (Bishop *et al.*, 2012). They have been implemented since the mid-20th Century to represent the landforms of a territory, emphasizing local geomorphological processes and geological peculiarities. Although a primordial geomorphological map was created by Gehne in the early 1900s (Gehne, 1912; fig. 1a), the first comprehensive vision of a geomorphological map was provided by Passarge (1914). However, Passarge's pioneering vision was initially rejected by the scientific community, which preferred a more literal description of landforms and features rather than a cartographic approach until the 1950s (Klimaszewski, 1963). After this period, one of the first significant attempts to produce an original geomorphological map was achieved by the Geographical Institute of the Polish Academy of Sciences (Klimaszewski, 1956) (fig. 1b). From the 1950s and the 1970s the cartographic approach spread in several other countries, which developed new legends and cartographic representations (Klimaszewski 1953, 1956; Savigear, 1965; Tricart, 1965; Demek and Commission on Morphological Survey and Mapping, 1971; Panizza, 1972; Demek and Commission on morphological survey and mapping, 1976). Similarly, in Italy, geomorphological maps began to gain prominence in the second half of the 20th Century. Notably, several authors have reviewed the history and evolution of this process (e.g., Castiglioni, 1982; Dramis and Bisci, 1998; Dramis *et al.,* 2005; D'Orefice and Graciotti, 2017; Campobasso *et al.*, 2021; D'Orefice and Graciotti, 2021).

These authors unanimously recognized the works of Mario Panizza as the first systematic geomorphological map in Italy (Panizza, 1966, 1968) (fig. 1c). Particularly, the geomorphological map by Panizza (1966) was realized using the most diffused geomorphological legends developed by Klimaszewski and Tricart in the 1960s (Klimaszewski, 1963; Tricart, 1965).

In the following years, the evolution of geomorphological maps and associated legends continued, led by various academic and non-academic working groups, until 1981 when the Geological Survey of Italy produced the first significant geomorphological maps (Servizio Geologico d'Italia, 1981, 1995; GNGFG - Gruppo Nazionale Geografia Fisica e Geomorfologia, 1986) (fig. 1d). Only in the 20th Century the launch of the national 'CARG Project' highlighted the need to introduce legislative measures and standardized criteria at the national level. This initiative aimed to draw guidelines for surveying the Italian Geomorphological Map at a scale of 1:50,000 (D'Orefice and Graciotti, 2017). Following the work of a dedicated commission, the results were published in the so called 'Quaderno 4' (Brancaccio *et al.*, 1994), which marked the beginning of the official Italian Geomorphological Mapping. After the development of some thematic maps (e.g., Servizio Geologico d'Italia e Regione Veneto, 2000; Servizio Geologico d'Italia e Regione Lazio, 2005), an updated version of the 'Quaderno 4', namely 'Quaderno 13' (Q13), was published later by Campobasso *et al.* (2018).

This updated version was aimed at enhancing and integrating the geomorphological legend, making it more feasible and implementable in GIS systems. In fact, GIS technologies opened up new perspectives in mapping approaches (Bishop and Shroder, 2004; James *et al.*, 2012), such as multi-scalability of data and completeness of geomorphological information, taking advantage from GIS vector data (Seijmonsbergen, 2013). By creating a specific database associated to each landform, it is possible to implement a series of morphological, morphometrical and other types of information that can be used in applied studies on geomorphological hazard and risk (Gustavsson *et al.*, 2006, 2008; Campobasso *et al.*, 2018).

Although it was clear from the development of the first geomorphological maps (Klimaszewski, 1956) that these thematic maps were intended for practical applications, e.g., directly serving local administrators to better understand and manage the territory, several challenges have arisen concerning their practical use.

If a geomorphological map is conceived as a static document (i.e., printed map) that represents the morphological situation of a given territory at the moment of its creation, but is not adaptable and implementable over time, it may quickly become outdated due to the evolution of the natural and anthropogenic processes (Bishop *et al.*, 2012). The potential of GIS solutions to solve these problems have been recognized since the late 1980s and 1990s, with early software experiments (Barsch and Zeiler, 1989; Mentlík *et al.*, 2006; Rădoane *et al.*, 2011; Kijowski *et al.*, 2012). Indeed, GIS systems allow for the representation of one or more specific themes by filling the geodatabase associated with the landform. Several geomorphological databases have been proposed over the years with the aim of integrating a wide range of scientific information (geological, geomorphological, hazard data etc.) into the attribute table of each landform (e.g., Gaspar *et al.*, 2004; Gustavsson *et al.*, 2006, 2008; Gustavsson, 2006; Mentlík *et al.*, 2006; Seijmonsbergen *et al.*, 2009; Magliulo and Valente, 2020; Carabella *et al.*, 2021; Forno *et al.*, 2022; Zervakou *et al.*, 2024).

In Italy, the proposal of a new geomorphological mapping model for application purposes (Campobasso *et al.*, 2021) marked the official adoption of the Geomorphological Database (GD) structure in the Italian Geomorphological Map. The GD structure includes various layers to represent both natural and anthropogenic landforms, subdivided by different vector geometries (polygon, polyline and point). In addition, it incorporates information on lithology, deposits, and other relevant data (fig. 2a).

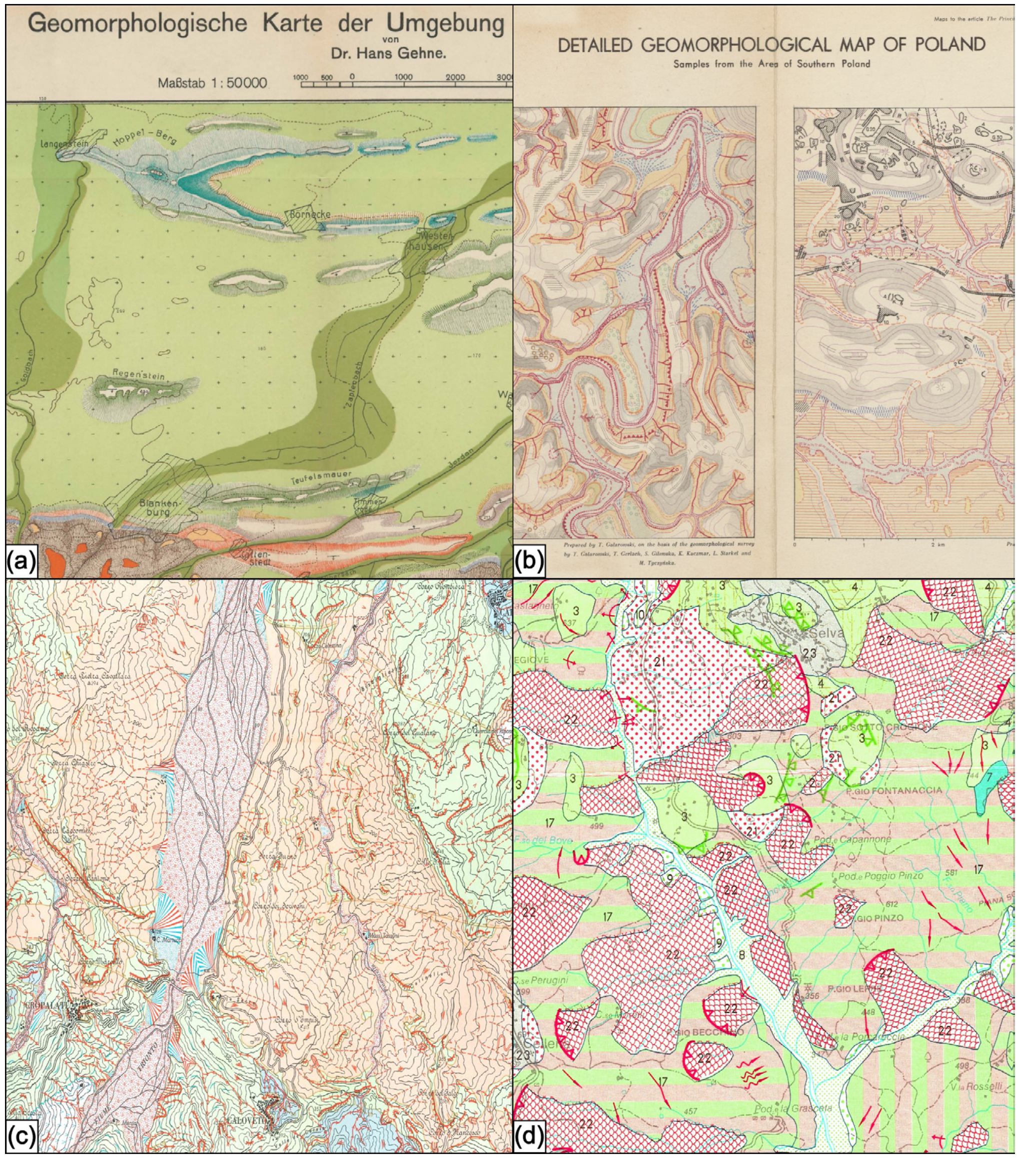

Figure 1 - Examples of geomorphological maps. (a) Excerpt of the 'Geomorphologische Karte der Unmgebund Thale am Harz' the geomorphological map by Gehne (1912), from https://opendata.uni-halle.de/; (b) Excerpt of the detailed map of Poland (Klimaszewski, 1956); (c) Excerpt of the 'Calopezzati' Geomorphological map (Panizza, 1966); (d) Excerpt of the 'Scansano' Geomorphological map (Servizio Geologico d'Italia, 1995).

This cartographic approach employs a unique code assigned to each mapped landform, allowing to differentiate between morphotypes (fig. 2b). Starting from further refinements of this digital cartographic approach, some authors subsequently developed hierarchical multiscale and full-coverage maps (e.g., Bufalini *et al.*, 2021; Valiante *et al.*, 2021; Forno *et al.*, 2022; Campobasso *et al.*, 2023). Although DB implementation opens up new perspectives towards the application of geomorphological maps, geomorphological surveys clearly reveal the issue of landforms overlapping in both landform assemblages and palimpsest landscapes (Fairbridge, 1968; Bauer, 2004) (fig. 2c). In this case it is necessary to define effective cartographic rules for surveying overlapped landforms and subsequently representing them on the map.

This problem becomes particularly evident when polygons need to be drawn over other polygons during detailed geomorphological surveys. For instance, as shown in fig. 2c, in case of a landslide deposit partially affected by rill-interrill erosion, the landforms derived by subordinate process (i.e., rill-interrill erosion) should be mapped as a polygon feature over the landslide polygon. However, to avoid topological incongruences due to overlapping landforms, rill-interrill erosion cannot be mapped as a polygon feature. Hence, rill-interrill erosion may alternatively be represented as points or linear features. However, a loss of information in certain areas is inevitable (fig. 2c).

In other words, while geomorphological layers assembled in a GIS environment can be easily overlapped to display different processes within the same area, where polygon stacking offers an immediate visualization approach, the final cartographic product must adhere to four conceptual and practical rules to ensure the readability and accuracy of the geomorphological data. Such kind of approach should allow to: i) respect topological rules between layers,

Type	Strata		Geometry and DB
Bedrock and soil information	Lithology St. 050	Weathering of soils St. 051	Polygon
Natural landforms	Landforms St. 052		Polygon/line/point
Anthropogenic landforms	Landforms St. 053		Polygon/line/point
Other symbols	Landforms St. 054		Polygon/line/point
Deposits	Deposits St. 055		Polygon

(a)

Code and landform name	Activity		Symbol geometry			Other elements of the DB
	A	R	polygon	line	point	
FD 6 - Surface affected by rill-interrill erosion	X					
GR 19 - Rotational slide body	X	X				

(b)

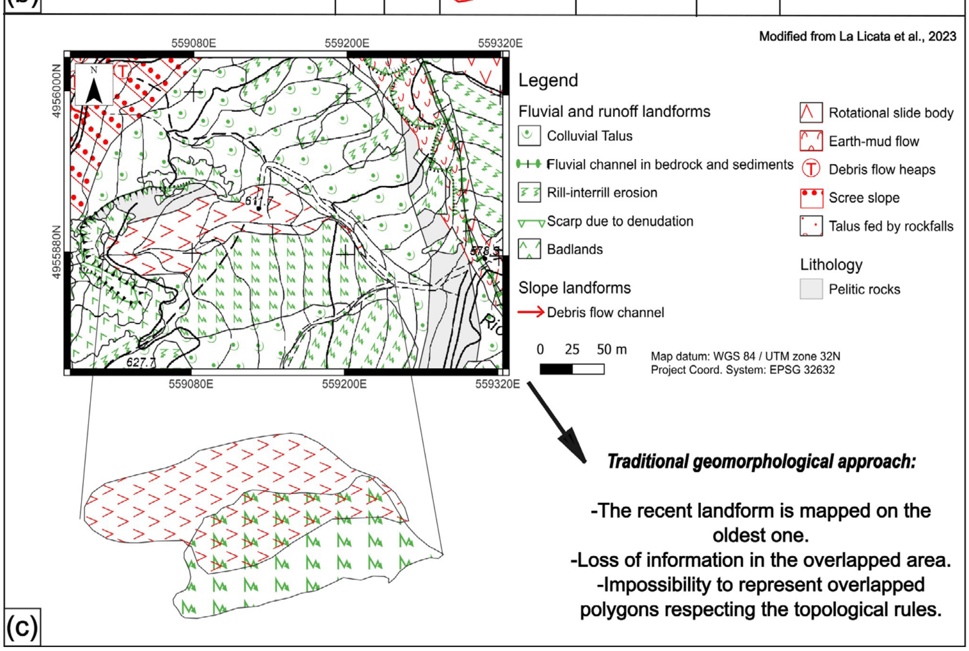

Figure 2 - Schematic and simplified representation of geomorphological mapping approach following (Campobasso *et al.*, 2021). (a) geomorphological database; (b) symbolism adopted for the representation of landforms-A=Active, R=Relict, DB=Geodatabase; (c) excerpt of geomorphological map and cartographic problems, modified from (La Licata *et al.*, 2023).

ii) overcome the arbitrary hierarchy definitions between layers, iii) avoid loss of information due to overlapped landforms, and iv) correctly derive associated thematic maps starting from complete geomorphological datasets.

The problem of the impossibility of exhaustively representing all the geomorphological elements present in the same area was highlighted also by Forno *et al.* (2022) and La Licata *et al.* (2025a). In this paper we propose a methodological framework aimed at overcoming this issue.

Our methodological approach relies on the implementation of a multi-strata geodatabase (MorphDB), enabling detailed mapping of each portion of the territory preferably using polygon features to represent landforms and deposits at high spatial resolution. This approach allows for the integration of geomorphological, textural, and topological information into a structured and searchable geodatabase. The methodology was tested within the upper Arda Valley (Northern Apennines, Italy), implementing the geodatabase provided by Italian Institute for Environmental Protection and Research (ISPRA; Campobasso *et al.*, 2021) in an ad-hoc field survey. Finally, the structured geodatabase was made available as dataset of Supplementary Materials. The presented methodology will open a new perspective on geomorphological mapping, avoiding cartographic errors and the loss of information in matched areas as well as enabling the production of derived maps exploitable for territorial planning.

STUDY AREA

The area selected to test the proposed methodology is located in the lower part of the upper Arda Valley (Northern Apennines, Italy; fig. 3a). In particular, the study area extends for ~5 km^2 and ranges from 350 m a.s.l. at the bottom of the Arda River to 835 m a.s.l. at the flanks of Mt. Zuccaro (figs 3a, 3b). The test area is intersected by the Arda River (fig. 3c), that drains the upper Arda Valley, and encompasses different landscape units, from alluvial plains to massif reliefs. In its lower part, the upper Arda Valley is largely characterised by a hilly and undulating morphology, where the gentle open slopes are affected by a set of geomorphic processes driven by gravity, water runoff and fluvial morphodynamics. These processes shaped the landscape by acting on the soft clayey sedimentary formations, where selective erosion and peculiar structural features accentuated the topographical discontinuity with steeper rocky reliefs made up of more resistant rocks (fig. 3b). The first synoptic geomorphological study of the upper Arda Valley was achieved by La Licata *et al.* (2023), who provided an overview of the variety of processes influencing sediment production and the related transport and deposition dynamics, in relation to geological and landscape features. Moreover, La Licata *et al.* (2025a) provided a comprehensive inventory map of sediment-related landforms and processes, highlighting where and to what extent these landscape features overlap and interact over various spatial-temporal scales, resulting in a highly morphodynamic landscape (La Licata *et al.*, 2025b). The upper Arda Valley can be considered an open laboratory to study complex and polygenetic geomorphic systems.

Moreover, the study area is characterised by sedimentary geological formations belonging to the External Ligurian Units (Servizio Geologico d'Italia, 1999), including: i) calcilutites and silty clays, ii) varicoloured clays and shales, iii) carbonate turbidites, and iv) arenaceous-pelitic turbidites (Martini and Zanzucchi, 2000; La Licata *et al.*, 2023).

The study area is characterised by several large- to small-size active landslides, talus and scree slopes deposited at the toe of higher turbiditic reliefs as well as paleo-landslides and paleo-surfaces (Dall'Aglio and Marchetti, 1988). In addition, several fluvial and runoff landforms are often associated with the main drainage network, although upland erosion frequently affects bare cultivated slopes. Landslides, bank erosion and surficial soil erosion are frequently associated to form complex hotspots of sediment sources with a high geomorphic hazard (La Licata *et al.*, 2025b) (figs. 3b, c). Furthermore, land degradation by rill-interrill, gullying, piping and badlands erosion largely determines the geomorphological setting in the study area, where the evolution of these landforms interacts with anthropic activities (figs 3d, 3e, 3f).

METHODS

General methodological framework

Different legends and mapping systems have been implemented over the years, enough to bring different cartographic products if different mapping systems are used (Otto *et al.*, 2011). The MorphDB is based on the official Italian guidelines for geomorphological mapping according to Campobasso *et al.* (2021), hereafter referred to as Q13. The database consists of a series of features structured with a searchable and implementable attribute table, allowing a full representation of the landforms that can be surveyed in the area of interest. We decided to develop our database starting from Q13 as it represents a solid base of data that can be implemented easily in any morphoclimatic context around the world. The landforms reported in Q13 are more than 370 and summarize a wide range of landforms and deposits that can be observed in Italy. However, the structure of the document is fully reflected in the associated geodatabase, allowing to implement new landforms easily, depending on the survey's necessity. In the past years some traditional geomorphological maps were produced in Italy and around the world starting from

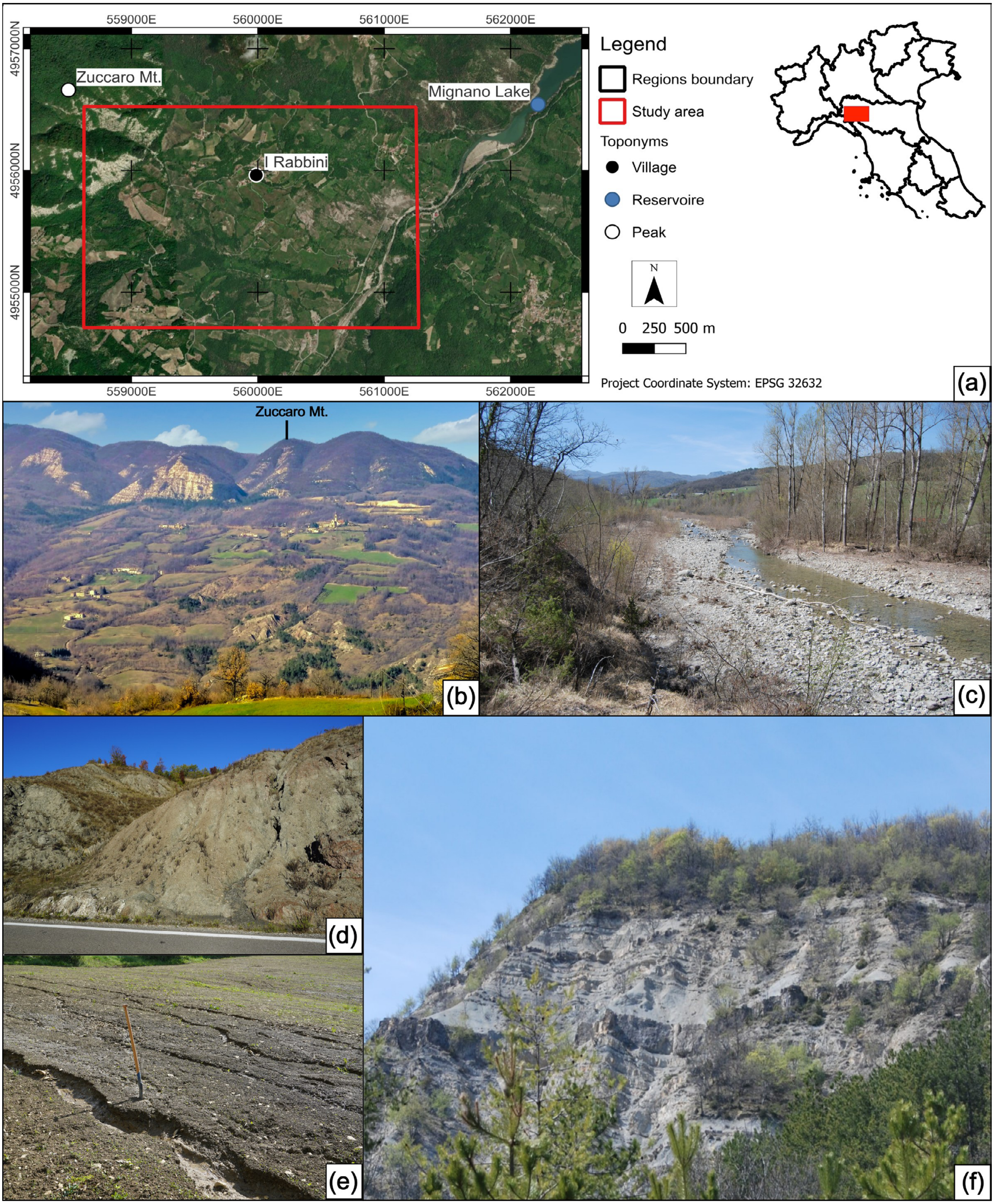

Figure 3 - Location of the study area within the upper Arda Valley (Northern Apennines, Italy). (a) study area (in the red box); (b) panoramic view of the study area showing hilly and gentle landscape (in the foreground) and higher and steeper reliefs (in the background); (c) the active bed of the Arda River with its alluvial plain; (d) Badlands in Cassio Varicoloured Clay affected by mudflow; (e) Severe rill-interrill erosion in an agricultural field; (f) Turbiditic Mt. Cassio Flysch Formation.

the Q13 (e.g., Bollati *et al.*, 2017; Bosino *et al.*, 2021; Brandolini *et al.*, 2021; Carton *et al.*, 2021; Faccini *et al.*, 2021; Raso *et al.*, 2021; Tognetto *et al.*, 2021; Pappalardo *et al.*, 2021; Prampolini *et al.*, 2021; Salvatore *et al.*, 2021 and references therein; Azzoni *et al.*, 2022; Forno *et al.*, 2022; Vergari *et al.*, 2022; Bonazzi *et al.*, 2023; Ferrando *et al.*, 2023; La Licata *et al.*, 2023; Shen *et al.*, 2023; Szatten *et al.*, 2023; Rashid *et al.*, 2024; Sassenroth *et al.*, 2024; Sumarmi *et al.*, 2024). However, nowadays the possibility of implementing landforms in a structured geodatabase opens for the possibility to produce detailed geomorphological maps, that can be in accordance or not, with the Q13 structure and related symbolisms.

The here presented MorphDB considers a flexible and easily applicable step-by-step approach, allowing to: i) define a mapping scale (≥1:10,000), ii) upload the MorphDB in a GIS system, iii) map the single geomorphological elements with the highest detail using polygon objects, iv) overcome the problem of overlapping polygonal landforms: if the same portion of slope is characterized by two different morphotypes (that can be both mapped as polygon), map the area and enrich the database with geomorphological information through different hierarchical levels (see next sections), v) integrate the geomorphological information that cannot be mapped in polygonal way (due to scale resolution) as polyline and/or point layers, vi) assemble the map prioritizing the most significative morphological information based on end-user demand.

The methodology followed in this study is represented in fig. 4.

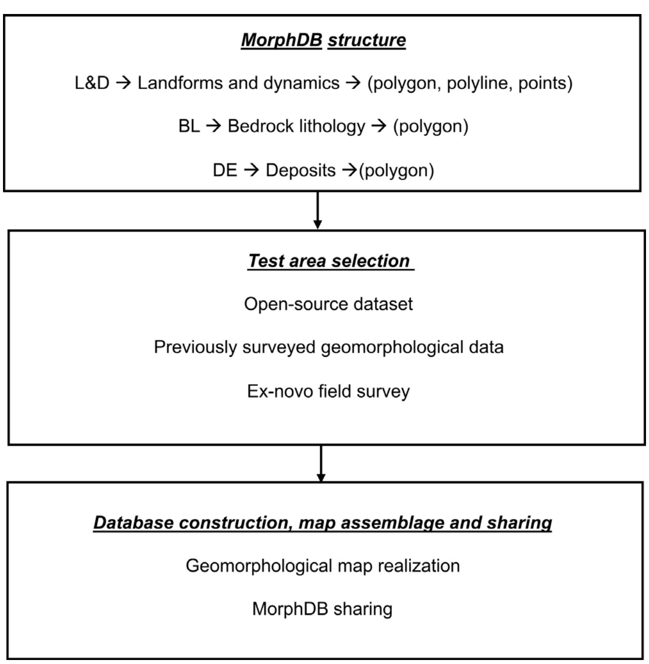

Figure 4 - Flowchart of the methodology.

MorphDB structure

The multi-strata geomorphological database structure was developed in a QuantumGIS environment (QGIS Version 3.40) starting from the ISPRA guidelines for the geodatabase implementation (Campobasso *et al.*, 2021) and implemented for our needs. It consists of a GeoPackage file that includes three features named 'L&D'-landforms and morphodynamics (fig. 5a), 'BL'-Bedrock lithology (fig. 5b), and 'DE'-Deposits (fig. 5c) as well as the respective domains (pre-filled fields to be selected from a drop-down list).

The 'L&D' strata consist of three features (L&D_polygon, L&D_polyline, L&D_points), containing all the mappable landforms and morphodynamics reported in the Q13. Differently than Campobasso *et al.* (2021), in these strata the subdivision between natural and anthropogenic related landforms, as well as a subdivision between landforms and the so called 'other symbols', was not considered. That is, in the MorphDB approach different landform levels do not need to be separated, as this approach allows for the representation of geomorphic information using polygon features simply implementing the attribute table of the polygon.

However, three different polygonal, linear and punctual layers were created, and a series of univocal fields were assigned (fig. 5a). Polyline and point integration are necessary if the mapping scale doesn't allow for a polygonal representation of the geomorphological element. The mandatory database fields (domains) are compiled according to the ISPRA guidelines (Italian national guidelines for geomorphological mapping (Campobasso *et al.*, 2021). Furthermore, these fields represent the minimum database to develop applications that start from geomorphological data (e.g., susceptibility models, geomorphological risk assessment, etc.).

The fields that compose the MorphDB are summarized in fig. 5 and described in detail in Supplementary Materials.

The MorphDB architecture can easily be created in GIS (fig. 5d) by adding the different fields in the attribute table for each feature. In addition, the structure can be reproduced several times for each different landform's levels, which overlap or underlap the highest mappable landforms (younger landforms) named LFD (fig. 5a). The LFD fields establishment follows the chronological order in landforms development (i.e., the landforms mapped in LFD-2 are older than LFD-1 etc.).

Finally, independently from the symbolism that will be used to represent the single morphotype stored in the MorphDB, its architecture allows to associate a series of information to each mapped landform, including a full morphological and morphometrical description with spatial-temporal consistency.

Test area selection

We select the upper Arda Valley as test area. The data utilized to implement the MorphDB derives primarily from (La Licata *et al.*, 2023, 2025a, 2025b), where we made field surveys, excerpts of geomorphological maps and a comprehensive inventory map of sediment sources and sink.

In addition, we integrated data from open-source databases. In particular, the Technical Regional Map at scale 1:5,000 (Regione Emilia-Romagna, 2020) was used as the basemap for geomorphological surveying. In addition, we acquired the Inventory of Landslide Phenomena in Italy (IFFI) data at a scale of 1:10,000 (APAT - Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici, 2007; Trigila *et al.*, 2010) available from the Emilia-Romagna region geoportal (https://geoportale.regione.emilia-romagna.it/). The geometric and morphological features of the landslides were checked and updated through dedicated field surveys, further refined on the map at 1:10,000. The field survey and GIS-based mapping procedure were conducted using a DELL Latitude 7220 Rugged Extreme Tablet. Finally, the available 5x5m Digital Terrain Model (DTM) (Regione Emilia-Romagna, 2019) was used to refine certain unaffordable areas within the study site.

Database construction, map assemblage, and sharing

All the acquired and/or surveyed geomorphological data were digitalized in QGIS by filling the MorphDB structure. In the 'L&D' polygonal stratum, we identified three LFD landform's levels. Subsequently, we assembled three distinct geomorphological maps at the scale of 1:5,000 scale. The level LFD, which represents the highest mappable landform (younger landform; fig. 5a), corresponds to the 'traditional geomorphological map'. The lower levels (LFD-1, LFD-2) represent landforms below the LFD. The final user has the possibility to select the proper LFD layer from the database based on the main goal they plan to reach. The symbology utilized for the maps follows the geomorphological legend proposed by (Campobasso *et al.*, 2021).

The MorphDB enables the identification of the morphological contributors acting on different levels within a defined surface by interrogating the respective polygon. The MorphDB architecture allows the implementation and the update of the landforms' database, if further processes will be activated in the surveyed area, creating new mappable landforms. In this case, the geomorphological information will be simply stored in an LFD+1 or +2 level.

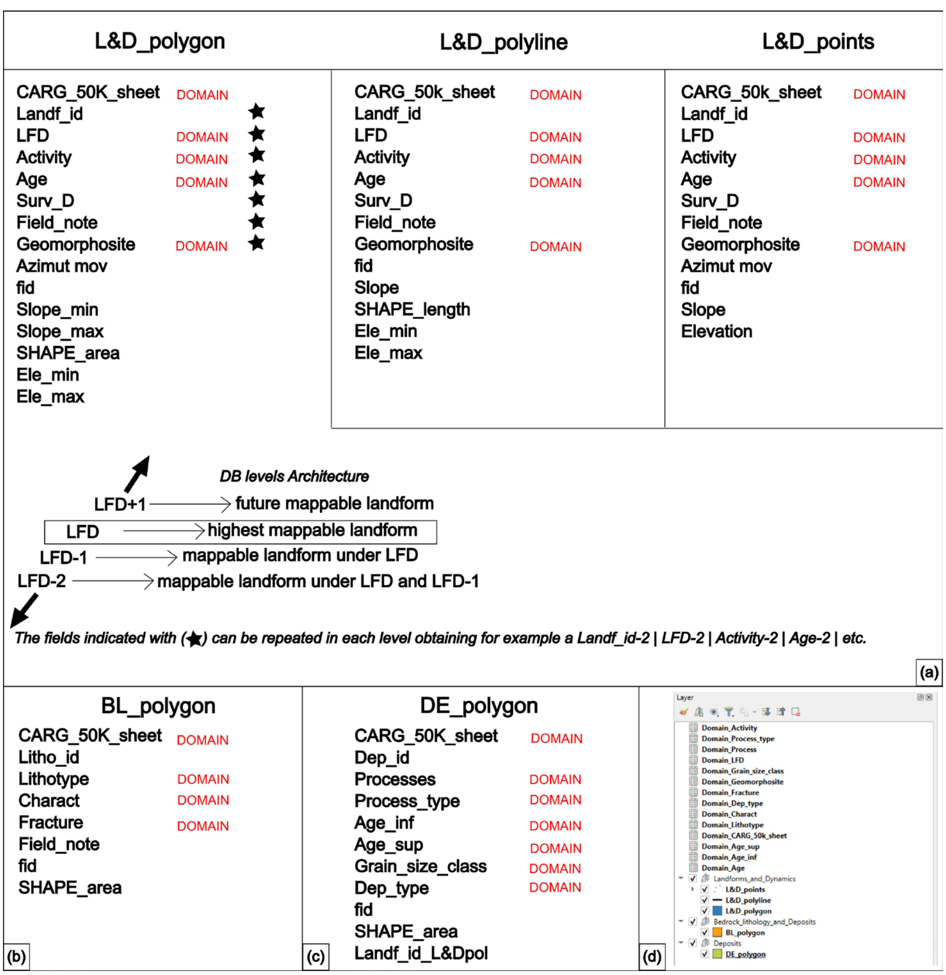

Figure 5 - Structure of the MorphDB: (a) strata containing landforms and morphodynamics; (b) stratum for bedrock lithology; (c) stratum for deposits; (d) .gpkg uploaded in QGIS.

The annex maps (Supplementary Materials) were reported to clarify the methodology, however, the MorphDB architecture is shared as GeoPackage file, freely downloadable and developable in the attachment of Supplementary Material.

RESULT AND DISCUSSION

The main objective of the multi-strata geomorphological database is to represent (in time and space) different geomorphological information detectable in a portion of territory (fig. 5). The structure of MorphDB was developed with a dual purpose, both to adapt the official Italian guidelines to field survey needs and to conduct analyses in the field of geomorphological hazard and risk assessment.

The entire structure of the MorphDB can be observed and downloaded in the *dataset* section of Supplementary Materials related to this article. Figure 6a shows an explanatory excerpt of a geomorphological map realized using the MorphDB structure. The full annex maps are available as Supplementary Materials. Each polygon is characterized by the attribute of all landforms mappable in the same area (fig. 6a), which are reported in the LFD column. In addition, the comparison between the MorphDB and the traditional geomorphological mapping approaches is shown in (figs 6b, c, d).

In order to respect the topology and hierarchy between landforms, in a traditional geomorphological map the last acting landform (upper one e.g., rill-interrill erosion), must clip the lower ones. Therefore, this often results in a loss of information when using polygon features (fig. 6c). To avoid polygon clipping, a change of geometry is necessary with the consequent uncertainty of the landform extension (rill-interrill erosion passes from polygon to points; fig. 6d on the right).

Therefore, the MorphDB can be considered a solution to preserve geomorphological information in the case of overlapping polygonal landforms (fig. 6b).

The construction of a detailed attribute table allows to solve the issue related to the spatial overlapping of landforms. For instance, both the maps represented in figs 6b and c – on the left – are composed of four different and not overlapped polygons. However, only in the first case (fig. 6b) the information in each portion of territory is not loss, since it is reported in several LFD levels in the attribute table. Conversely, in the traditional mapping approach each polygon carries information about one single landform (e.g., the represented area is affected by rill-interrill erosion).

Furthermore, this approach allows to further integrate geomorphic features later surveyed on previously implemented databases, thereby reducing working time and increasing geomorphological detail. For instance, if a new rill-interrill erosion area is activated on a preexisting landslide, the information related to the newly surveyed landform can be added in the level LFD+1, specifying the characteristics of the later landform in the database. The implementation of the database opens up the possibility to quickly update the map with new data coming from different sources (e.g., field surveys, remote sensing, literature etc.) by integrating them into the pre-existing geomorphological base level allowing also to keep track of the evolution of morphogenetic processes in the area.

In the case reported in fig. 6, and further presented in fig. 7, an anthropogenic surface lies on a fluvial erosion surface superimposed on a landslides toe. This surface might have completely different applicative meanings if the lower landform (landslide) is considered or not. In the first case, the anthropogenic surface is sited on: i) a relict fluvial landform (i.e., fluvial erosion surface), where a flooding event will not reach the area and ii) an active landslide body that can be reactivated, for example, by intense rainfalls or earthquakes (fig. 7a). Conversely, if the underlaying landslide is not adequately represented, the potential geomorphic risk related to the anthropogenic landform might be underestimated as the uppermost landform would overlay a relict fluvial erosion surface (fig. 7b). This concept finds practical application especially in areas where villages were built on the top of large-scale landslide bodies sensu (Hungr *et al.*, 2014; Bertolini *et al.*, 2017), which have been reshaped by recent morphogenetic processes but could be reactivated with uncertain return times (Bertolini *et al.*, 2005; Bertolini and Pizziolo, 2008; fig. 6a and 7c). The problem of representing many surveyed geomorphological landforms on a single map was emphasized for a long time (Demek, 1976). In addition also Forno *et al.* (2022) highlight the problem applying a full coverage, object base method to overcome the issues of traditional geomorphological mapping approaches. However, the multiscale representation of geomorphological data in GIS environment allows the geomorphological detail to increase in a certain part of slope (La Licata *et al.*, 2025a).

As specified by other authors, e.g. (Otto and Smith, 2013) a geomorphological map can act as a basic tool for land management as well as geomorphological and natural hazard assessment, however, the final purpose is subjected to the cartographic rules chosen during the survey. Even if there isn't a single approach to geomorphological mapping (Lee, 2001), the concept at the base of detailed geomorphological surveys aimed at producing a traditional geomorphological map is to map, with the highest degree of detail, the «relief forming processes controlling the primary foundation and the total geomorphological character of the present surface forms independently on their later degradation of modelling». The latter are «then mapped in according to the symbols of specific genetic groups, thus the polygenic and polycyclic character of the present-day surface forms can be stressed» (Demek and Commission on Morphological Survey and Mapping, 1971). In other words, all the landforms and deposits of a territory should

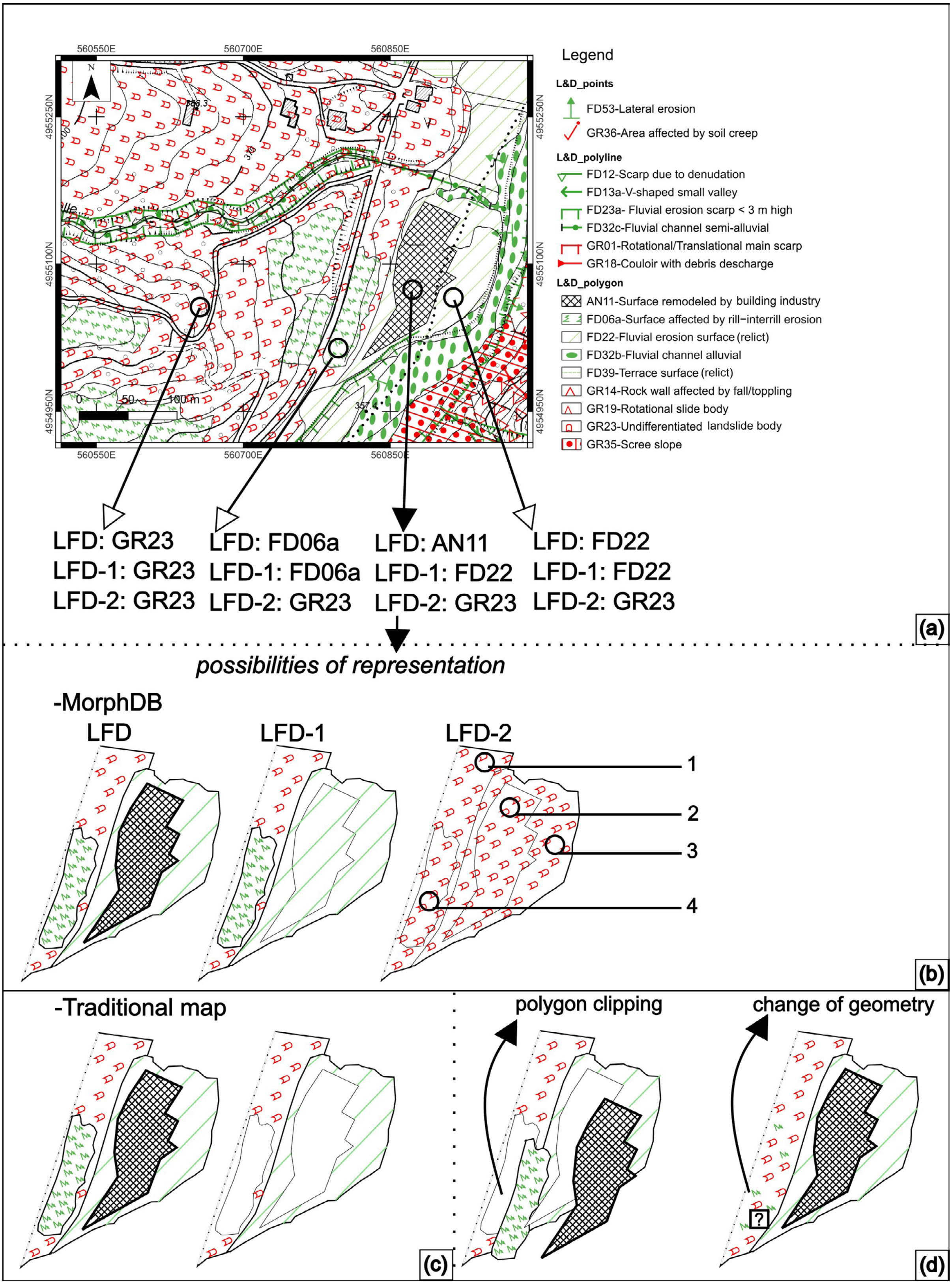

Figure 6 - Excerpt of geomorphological map realized with MorphDB: (a) geomorphological map with and extract of the attribute table indicating the different LFD levels; (b) MorphDB representation possibilities; (c and d) traditional map representation possibilities.

be considered and mapped in individual genetic groups. As specified by (Castiglioni, 1982) the latest modeler processes should be prioritized, independently by its intrinsic applicative meaning. A rill-interrill surface that completely affects an ancient landslide body should be mapped as the last occurred process. Conversely, it should be avoided/simplified, in geometric terms, to prioritize the landslides and highlight the main morphogenetic process (Castiglioni, 1982). Starting from a traditional geomorphological map, it is possible to derive applicative maps only if all geomorphological information for each portion of slope is initially surveyed and stored without any simplification of landforms. Thus, by filling in the MorphDB, it is possible to store all the information related to each mapped landform, allowing end-users to choose which landform to prioritize depending on specific purposes (e.g., application, scientific, or geo-touristic purposes).

The problem of the spatial and temporal relations between objects (landslides, in particular) was highlighted also by (Valiante *et al.*, 2021) who developed a database structure capable of storing both spatial and temporal information related to a single geomorphological dataset with potential practical applications (Dramis *et al.*, 2022). Later, other authors developed guidelines to apply a full coverage, hierarchical and multi-scale geomorphological mapping models, defining a series of levels capable to differentiate the single morphologies (Guida *et al.*, 2012; Bufalini *et al.*, 2021; Valiante *et al.*, 2021; Forno *et al.*, 2022; Campobasso *et al.*, 2023).

The MorphDB approach proposed in the present study plans to digitalize the landforms surveyed in the field, subsequently checking them with the traditional stereo-orthophotos interpretation or DTM analysis following the "traditional" geomorphological approach and infilling the specific database. The simplification respect to (Campobasso *et al.*, 2021) does not lead to a reduction of geomorphological information and does not violate the topological aspects of representation. On the contrary it overcomes the problem of representing overlapped landforms without changing the extension or the geometry of the layers. The 'L&D' strata fully represent each landform on an area within different hierarchical multi scale levels (Bufalini *et al.*, 2021). In this way landforms due to the secondary or subordinate processes sensu (La Licata *et al.*, 2025a, 2025b) can be mapped as polygonal features on others, depicting the maximum available geomorphological information. In addition, it is always possible to split the new information layers to refer to those provided for by Campobasso *et al.* (2021).

MorphDB is thought to address the most detailed information in a large-scale representation (≥1:10,000) digitalizing features preferably with polygonal geometry. However, the points and polyline strata make it possible to overcome multiscale representation problems. In this case, polylines or points acquire added detail value, as well as simplify overlapping shapes.

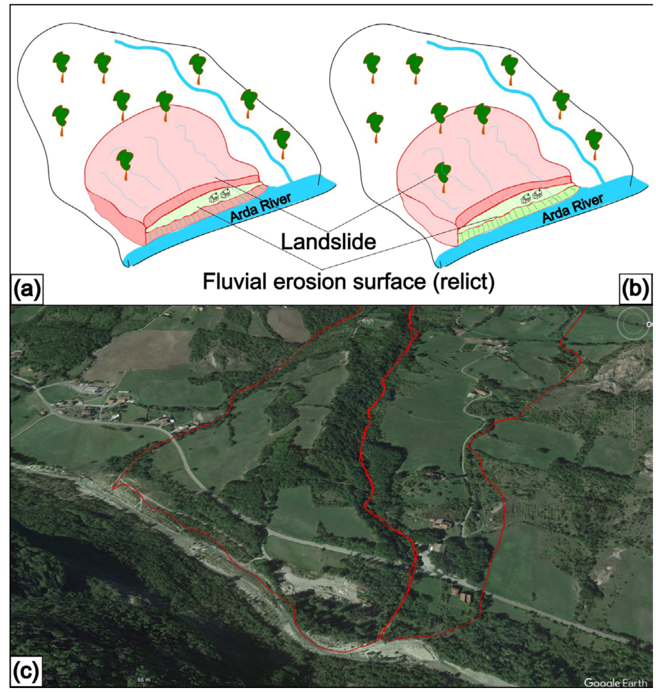

Figure 7 - (a and b) sketches of landscape representing an anthropic area on natural features; (c) Google Earth image representing landscape of landslides, typical of several Apennines context.

The legend of Italian geomorphological mapping (Campobasso *et al.*, 2021) is rich of landforms and deposits related to different morphogenetic agents. However, it can be used to survey territories in a variety of morphoclimatic settings by implementing the missing morphotypes in the database. Several cases studies where the Italian legend was adopted abroad are nowadays present in the literature (e.g., Bosino *et al.*, 2021; Prampolini *et al.*, 2021; Azzoni *et al.*, 2023; Shen *et al.*, 2023; Szatten *et al.*, 2023; Sassenroth *et al.*, 2024; Sumarmi *et al.*, 2024). Therefore, the MorphDB can be utilized to produce geomorphological maps starting from solid and shared criteria and might promote a wider diffusion of the Italian legend (Campobasso *et al.*, 2021).

CONCLUSION

In this study we propose a novel mapping methodology, namely MorphDB, which is aimed at addressing the need to account for overlapping landforms in geomorphological mapping. Our approach ensures the preservation of topology and reduces the need to represent only the most significant/younger morphologies in the case of polygenic and palimpsest landscapes. The methodology was successfully tested in the Northern Apennines and in the future will be applied in others morphological contexts in order to achieve further improvements and address potential limitations of the method. The flexibility of MorphDB allows for the detection of polygon layers, which can be mapped in both time and space, without losing geomorphological information and enabling integrations and updates.

The MorphDB will provide help in the creation of geomorphological databases as well as facilitate the exchange and comparison of geomorphological data among researchers. The database proposed in this paper, created with GIS system, allows us to represent all the mappable elements of a certain terrain unit (e.g., portion of slope) evaluating all the landforms and deposits occurring on different spatial-temporal scales in the mapping unit.

SUPPLEMENTARY MATERIALS

Supplementary materials associated with this article, including *An example from the upper Arda Valley, Northern Apennines, Italy* of a geomorphological map with the associated multi-strata geomorphological database (MorphDB) can be found in the online version, at https://www.gfdq.glaciologia.it/index.php/GFDQ/libraryFiles/downloadPublic/7.

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