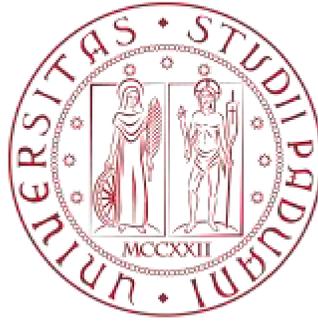SCUOLA DI SCIENZE

Dipartimento di Geoscienze

Direttore Prof. Nicola Surian

MASTER DEGREE IN

ENVIRONMENTAL GEOLOGY AND EARTH DYNAMICS

GEOSPATIAL ANALYSIS AND HYPERSPECTRAL CLASSIFICATION OF SOIL UNITS AND PALEO-RIVERBEDS BETWEEN THE ASTICO AND BRENTA BASINS IN THE VENETO PROXIMAL PLAIN

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CONTENTS

LIST OF ABBREVIATIONS

ARPAV   -   Agenzia Regionale per la Protezione dell'Ambiente del Veneto

DEM   -   Digital Elevation Model

DSM   -   Digital Surface Model

DTM   -   Digital Terrain Model

ETRA   -   Energia Territorio Risorse Ambientali (company from Rubano (PD))

LiDAR   -   Light Detection and Ranging

PNRR   -   Piano Nazionale di Ripresa e Resilienza

UAV   -   Unmanned Aerial Vehicle

Abstract

This thesis investigates an integrated geospatial methodology for soil classification and geomorphological analysis between the Astico and Brenta basins in the Veneto proximal plain, with a focus on the role of paleorivers in shaping current soil distribution. The work was developed as part of the IPERLAND project, in collaboration with ETRA, and addresses significant challenges in environmental monitoring, land planning, and soil mapping. The main objective is to overcome existing limitations in traditional soil classification, which might partly oversee the influence of buried or relict riverbeds, by integrating hyperspectral and LiDAR data with open-source QGIS and ENVI. The Veneto region, characterized by complex sedimentary dynamics and intensive anthropogenic transformation, is an ideal case study for the development of advanced mapping methodologies. Hyperspectral remote sensing, due to its high spectral resolution, enables the identification of subtle mineralogical and textural differences in the soil. Combined with LiDAR-derived Digital Terrain Models (DTMs), which reveal microtopographic variations, this approach allows for the detection of paleoriver channels and the interpretation of fluvial processes over geological time. The study emphasizes the importance of mapping these features as they are closely linked to soil genesis, hydrology, and vegetation patterns. The methodology includes a semi-automated workflow for image stacking, pre-processing, spectral masking, and classification. Soil units are identified based on VNIR and SWIR hyperspectral signatures, focusing on properties such as clay content, carbonate presence, and organic matter. Vegetation and urban features were masked using indices such as MSAVI2 and custom thresholding techniques to isolate natural soil surfaces. Furthermore, thematic maps were produced to highlight correlations between soil units, geomorphological features, and potential flood-prone areas. These outputs were validated through comparisons with ARPAV soil maps and field observations, enhancing the reliability and reproducibility of the results. A key contribution of the study is the mapping of paleorivers, which were delineated through combined spectral and terrain analysis. These features, in some cases undetectable through conventional aerial imagery, provide critical information for reconstructing the historical evolution of the landscape. Their recognition improves the understanding of sediment transport, soil fertility gradients, and water retention zones. The thematic maps generated within this work are intended to support sustainable land use planning, agricultural development, and hydrological risk assessment.

By combining advanced remote sensing tools with accessible GIS technologies, this thesis presents a replicable model for high-resolution environmental mapping. The approach is scalable, cost-effective, and suitable for application in diverse geographic contexts. Overall, the work highlights the relevance of integrating geomorphological history into modern environmental studies and contributes to the advancement of digital soil mapping techniques in Italy and the whole world as well.

Riassunto

Questa tesi indaga una metodologia geospaziale integrata per la classificazione dei suoli e l'analisi geomorfologica tra i bacini dell'Astico e del Brenta, nella pianura prossimale veneta, con particolare attenzione al ruolo dei paleoalvei nella modellazione della distribuzione attuale dei suoli. Il lavoro è stato sviluppato nell'ambito del progetto IPERLAND, in collaborazione con ETRA, e affronta sfide significative legate al monitoraggio ambientale, alla pianificazione del territorio e alla mappatura dei suoli. L'obiettivo principale è superare i limiti delle classificazioni pedologiche tradizionali, che talora possono in parte trascurare l'influenza di letti fluviali sepolti o relitti, attraverso l'integrazione di dati iperspettrali e LiDAR con software open-source come QGIS ed ENVI. La regione Veneto, caratterizzata da complesse dinamiche sedimentarie e da un'intensa trasformazione antropica, rappresenta un caso di studio ideale per lo sviluppo di metodologie avanzate di mappatura. Il telerilevamento iperspettrale, grazie alla sua elevata risoluzione spettrale, consente di individuare sottili differenze mineralogiche e tessiturali nei suoli. Combinato con i Modelli Digitali del Terreno (DTM) derivati da dati LiDAR, che evidenziano variazioni microtopografiche, questo approccio permette di rilevare i paleoalvei e interpretare i processi fluviali su scala geologica. Lo studio sottolinea l'importanza della mappatura di queste caratteristiche, strettamente collegate alla genesi dei suoli, all'idrologia e ai pattern vegetazionali. La metodologia include un flusso di lavoro semi-automatizzato per lo stacking delle immagini, la pre-elaborazione, il mascheramento spettrale e la classificazione. Le unità pedologiche sono identificate sulla base delle firme spettrali VNIR e SWIR, con particolare attenzione a proprietà come il contenuto di argilla, la presenza di carbonati e la materia organica. Vegetazione e aree urbanizzate sono state mascherate utilizzando indici come l'MSAVI2 e tecniche di thresholding personalizzate, al fine di isolare le superfici naturali del suolo. Inoltre, sono state prodotte mappe tematiche che evidenziano le correlazioni tra unità pedologiche, elementi geomorfologici e potenziali aree soggette ad allagamento. Questi risultati sono stati validati mediante confronti con le carte dei suoli ARPAV e osservazioni di

campo, aumentando l'affidabilità e la riproducibilità dell'approccio. Un contributo chiave dello studio è la mappatura dei paleoalvei, delineati attraverso l'analisi combinata dei dati spettrali e altimetrici. Tali elementi, talora non del tutto visibili con l'aerofotogrammetria tradizionale, forniscono informazioni fondamentali per ricostruire l'evoluzione storica del paesaggio. Il loro riconoscimento migliora la comprensione del trasporto sedimentario, dei gradienti di fertilità del suolo e delle zone di ritenzione idrica. Le mappe tematiche prodotte in questo lavoro sono concepite per supportare una pianificazione del territorio sostenibile, lo sviluppo agricolo e la valutazione del rischio idrologico. Combinando strumenti avanzati di telerilevamento con tecnologie GIS accessibili, questa tesi presenta un modello replicabile per la mappatura ambientale ad alta risoluzione. L'approccio è scalabile, economicamente sostenibile e applicabile in contesti geografici differenti. Complessivamente, il lavoro evidenzia la rilevanza dell'integrazione della storia geomorfologica negli studi ambientali contemporanei e contribuisce al progresso delle tecniche di mappatura digitale dei suoli in Italia ed altrove in ambienti analoghi.

INTRODUCTION

1.1 State of the art

The Veneto fluvial plain, located in northeastern Italy, represents a dynamic and complex landscape shaped by millennia of fluvial, geological, and anthropogenic processes (Mozzi et al., 2010). This vast lowland, extending from the Alps to the Adriatic Sea, has been historically influenced by major rivers such as the Po, Adige, Brenta, and Piave, which have played a crucial role in sediment transport, land formation, and human settlement patterns. Today, the region faces significant environmental and socio-economic challenges, including land subsidence, hydrological changes, and anthropogenic pressure (Pijl et al., 2018). In particular, soil classification and land use changes pose major concerns due to the increasing difficulty in distinguishing and managing different soil types, which are critical for agricultural productivity, infrastructure planning, and environmental conservation (Prosdocimi et al., 2013). One of the fundamental properties used in soil classification is particle size, as it can be determined through relatively simple and easily interpretable methods. Consequently, arbitrary particle size scales for distinguishing between sand, silt, and clay have been widely accepted.

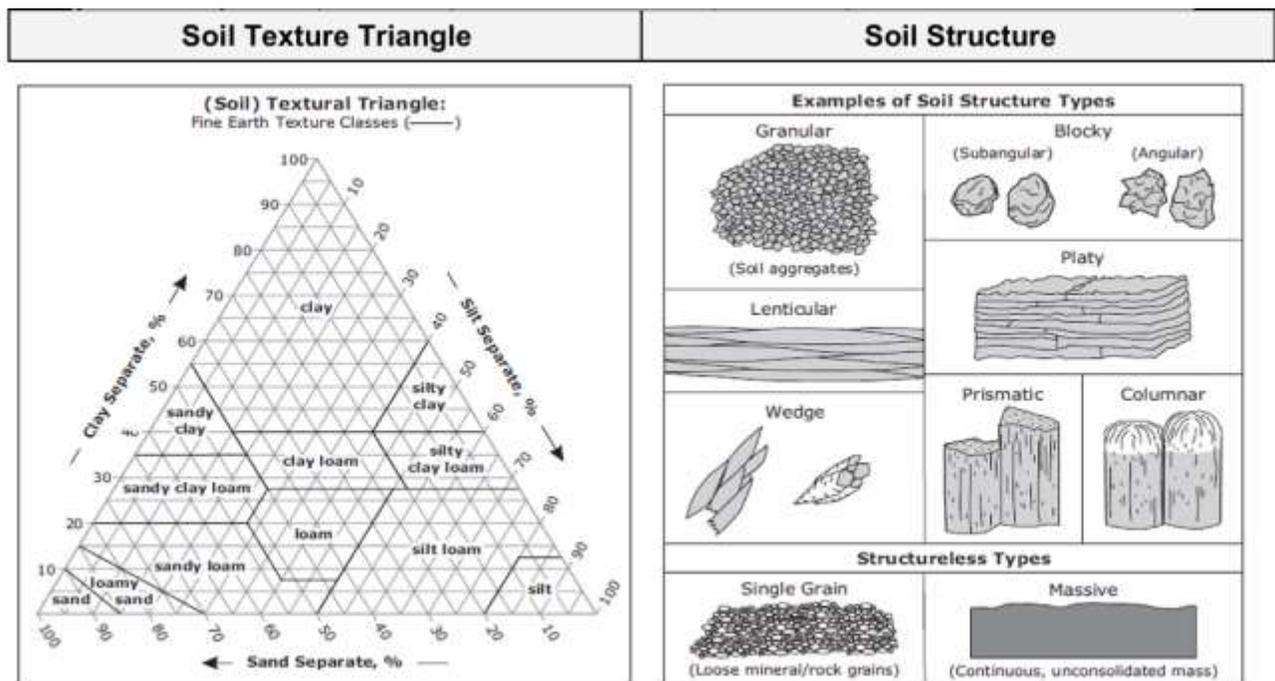This is exemplified by the well-known USDA soil texture triangle (Fig.1).

Figure. 1. Soil classifications compared in this study: texture triangle (USDA, Soil Science Division Staff, 2017)

Soil mapping typically involves a detailed field survey that requires an accurate description of the area and the soil profiles. Traditional soil surveys are often based on extensive field observations (which can sometimes be subjective) and subsequent laboratory analyses that provide valuable insights into the soil characteristics. Notably, remote sensing technology now plays a crucial role in enhancing soil surveys (Kaliraj et al., 2024; Mondal et al., 2024).

The most effective remote dataset for landscape analysis is LiDAR data and multi- and hyperspectral images acquired from both aerial and satellite platforms.

One of the appealing features in the LiDAR output is the direct availability of three-dimensional coordinates of points in object space. Airborne LiDAR provides direct three-dimensional coordinates of ground returns and has become a primary source for high-resolution digital terrain information used in geomorphology, hydrology, archaeology and soil mapping (Habib et al., 2005; Raber et al., 2007). For floodplain and paleo-fluvial studies, LiDAR-derived digital terrain models (DTMs) are particularly valuable because they reveal subtle microreliefs (levees, abandoned channels, oxbows, terraces) that are often not visible in conventional topographic products (Habib et al., 2005). In particular, LiDAR data have become a major source of digital terrain information (Raber et al., 2007) and have been used in a wide of areas, such as building extraction and 3D urban modelling, hydrological modelling, glacier monitoring, landform or soil classification, river bank and coastal management, and forest management (Habib et al., 2005).

Italy's public LiDAR holdings and regional archives show a range of delivered DTM raster resolutions that depend on the survey campaign, sensor, and processing choices:

- **Veneto Region:** The regional LiDAR archive provides harmonized DTM tiles for most of the region; the portal currently offers a principal DTM at 5 m cell size for broad download, while higher-resolution products (1 m or 2 m) exist for many flights and specific areas. Where available, a 1 m DSM / DTM exists from Ministry-sponsored campaigns and regional flight projects (https://idt2.regione.veneto.it/). In addition to these public datasets, this thesis also made direct use of ETRA survey LiDAR data acquired during the IPERLAND Project, which provided high-resolution terrain data focused on the study area.

- **Other Northern Italian regions:** Friuli-Venezia Giulia has public 0.5 m DTMs for selected zones, and national products include many 1 m DTM tiles for the alpine and pre-alpine domains. Large-scale national compilations or PNRR/PNRR-linked efforts are producing harmonized 5 m DTMs for Italy as a whole, while local high-resolution tiles remain available where campaigns were denser (Vanzani et al., 2025).

During the 1970s, multispectral remote sensors with a limited number of broad spectral bands were developed to monitor natural resources (Goward et al., 2022). However, these multispectral images faced significant limitations in various applications, prompting the need for more advanced imaging systems with higher spectral resolution. This demand led to the development of hyperspectral imaging systems, a result of advancements in imaging spectroscopy. The evolution of these systems was enabled by rapid technological progress in detectors, optical design and components, atmospheric radiative transfer, and data processing capabilities.

Hyperspectral remote sensing has the ability to collect data across numerous contiguous narrow spectral bands of the electromagnetic spectrum. These bands cover regions from visible and near-infrared (VNIR) to shortwave infrared (SWIR), achieving high spatial and spectral resolutions (Shukla and Kot, 2016).

Hyperspectral data can be classified based on the platform type, encompassing non-imaging or imaging in situ measurements, airborne imagery, and space-borne imagery. Hyperspectral images often contain thousands or even millions of data points.

Using hyperspectral imagery to map paleorivers involves leveraging the unique spectral properties of surface materials to identify and analyze ancient river systems. Hyperspectral sensors capture data across numerous, narrow spectral bands, providing detailed information about the mineralogical and compositional characteristics of the Earth's surface (Peyghambari and Zhang, 2021; Francos et al., 2024). This capability is particularly advantageous for studying paleorivers, as these ancient channels often leave subtle geomorphological and sedimentary signatures that can be challenging to detect through conventional mapping techniques. In Northern Italy and elsewhere, hyperspectral applications have already shown success. For example, in mapping clay content over agricultural soils in the ETRA survey campaign of 2022, using airborne hyperspectral data.

1.2 Goals and motivations

The Veneto fluvial plain faces critical challenges, including climate change-induced variations in precipitation, increasing frequency of extreme weather events, and rising sea levels that threaten coastal areas. The integration of micro-relief DEM, hyperspectral imaging, and GIS analysis provides new opportunities to enhance environmental monitoring and develop adaptive strategies for land and water resource management.

This thesis addresses a critical gap in soil classification by integrating paleoriver and riverbed data using QGIS. By recognizing the impact of historical fluvial systems on soil distribution, this research contributes to more accurate and comprehensive soil mapping, which is essential for agriculture, environmental conservation, and land-use planning. The use of QGIS ensures that the methodology is accessible and reproducible, allowing for broader applications in different geographical contexts. By employing hyperspectral imagery, researchers can achieve high-resolution and precise identification of paleoriver systems, offering a valuable tool for geomorphological, archaeological, and environmental applications. Ultimately, this study highlights the importance of considering geological history in soil science and demonstrates the potential of GIS technologies in advancing interdisciplinary research in geomorphology and environmental management.

The thesis is part of the IPERLAND project, which focuses on enhancing the environmental understanding of the ETRA service area through advanced geospatial technologies. The core objective is to improve soil classification by incorporating paleo-hydrological features such as relict riverbeds into a QGIS-based mapping methodology. Traditional soil classification often overlooks the influence of historical fluvial systems, limiting the accuracy of environmental and agricultural assessments. To address this gap, the study developed semi-automated workflows using ENVI and QGIS to process hyperspectral and LiDAR datasets, enabling the extraction of high-resolution thematic maps. These maps include soil composition (clay-rich, carbonate-rich, organic-rich), thereby providing a refined understanding of soil genesis and distribution.

The methodology also integrates terrain analysis from LiDAR-derived DEMs to identify paleo-channels and geomorphological controls on surface processes. Validation was conducted through comparison with pre-existing ARPAV soil maps and regional geological data. The findings contribute to improved soil

mapping accuracy and highlight the influence of paleoriver systems on present-day soil characteristics. Moreover, by leveraging accessible open-source tools, the study ensures methodological reproducibility and scalability across different regions and research contexts.

One of the critical knowledge gaps in soil classification studies is the understanding of how historical paleorivers and riverbeds influence present-day soil distribution. Many existing studies focus on contemporary hydrological features, often overlooking the impact of ancient river systems that shaped the geomorphology and soil characteristics of a region. This gap in knowledge limits the accuracy of soil classification models, especially in areas where buried or relict fluvial features play a significant role in soil formation.

This study aims to address this gap by developing a QGIS-based methodology to classify soils while incorporating paleorivers and riverbeds as distinct layers in the mapping process. By integrating geological and hydrological data, the research will provide a more comprehensive understanding of soil distribution patterns and their historical influences.

A study like this is essential for improving soil classification accuracy, particularly in regions where past fluvial activities have left a significant imprint on the landscape. The findings will be valuable for agricultural planning, environmental conservation, and land development projects that require precise soil information. Furthermore, the use of QGIS ensures accessibility and reproducibility, making the methodology applicable to various regions and research contexts.

The IPERLAND project was developed with the primary aim of enhancing the spatial understanding and environmental characterization of the ETRA service area through the integration of hyperspectral and LiDAR data. The motivation stemmed from the need to improve the existing Sistema Informativo Territoriale (SIT) or Territorial Information System or more commonly in English, Geographic Information System (GIS) for the evaluation of residual war risk and for broader environmental and infrastructural applications. In particular, the project sought to address existing limitations in soil and land surface mapping by exploiting high-resolution geospatial datasets acquired during recent aerial and UAV campaigns.

Traditional soil maps, such as those produced by ARPAV, lack the resolution and thematic accuracy required for detailed environmental analysis and land management. At the same time, the potential of hyperspectral imagery, especially in the VNIR and SWIR spectral ranges, remains largely untapped in regional planning efforts. The IPERLAND project was motivated by the opportunity to implement advanced remote sensing techniques to extract critical information related to soil composition, vegetation status, and surface water content.

In addition, the project was driven by the urgent need for sustainable resource management in the context of climate change, with a particular focus on monitoring vegetation health, identifying areas of water retention, and supporting water infrastructure planning in geologically complex regions like the Altopiano dei Sette Comuni and the plains between the Brenta and Bacchiglione rivers.

By narrowing the scope to a selected area of the ETRA territory, this study aims to demonstrate the effectiveness of hyperspectral and GIS tools in producing high-resolution, thematically rich soil and surface classifications. These results can directly support land use planning, environmental monitoring, and future modeling of hydrological behavior in the region.

This thesis project was developed as a focused contribution to the broader IPERLAND research initiative and aims to explore the potential of hyperspectral and GIS-based techniques for soil characterization and paleo-hydrological analysis. The specific goals of this study are as follows:

1. Development of a Semi-Automated Workflow for Image Analysis: To create robust, automated workflows for the preprocessing and analysis of hyperspectral data using ENVI and QGIS for the classification of land surfaces. These workflows enabled the stacking, filtering, and processing of hyperspectral imagery to extract thematic information with higher informative value, to enhance exposed soil surfaces based on hyperspectral indices, using masking techniques to exclude vegetation, urban areas, and infrastructure. The study focuses particularly on the identification of carbonate-rich and clay-rich soil units. In addition, the main step carried out was the stacking of VNIR and SWIR rasters to ensure their joint use in subsequent analyses. This stacking procedure provided spectrally and spatially consistent imagery, suitable for integration with ancillary datasets

(LiDAR-derived DTM, ARPAV soil maps, and vector layers from the Veneto Region Geoportal).

2.   Hyperspectral   Data   Preparation   and   Integration:
To preprocess and align airborne hyperspectral datasets (VNIR and SWIR), ensuring spatial coherence between different acquisition dates and sensors. This includes radiometric corrections, geometric alignment, and data stacking procedures required to obtain spectrally and spatially consistent imagery. In this thesis images just were stacked.

3.   Generation   of   Thematic   Environmental   Maps:
To produce a suite of thematic raster and vector maps including:

The use of mineralogical spectral indices (CAI, CALI, CLAI) in soil composition maps, resulting in distinguishing clay, carbonate, and mixed soils;

4.   Paleoriverbed   Mapping   and   Terrain   Interpretation:
To identify and map possible paleo-channels and fluvial morphological features through the combination of terrain analysis (from LiDAR-based digital elevation models) and spectral signatures, contributing to the understanding of sedimentary dynamics and soil genesis in the region.

5.   Validation   and   Interpretation   of   Results:
To correlate the classified soil and geomorphological units with pre-existing thematic layers such as the ARPAV Soil Map and regional geomorphological data. This serves to validate the method and interpret the environmental and geological significance of the findings.

1.4. Thesis' structure

The structure of this thesis follows a logical progression that reflects both the scientific objectives and the methodological development of the study. After a chapter presenting the theoretical and regional framework, describing the geological, geomorphological, and hydrological context of the study area within the ETRA territory, a methodology chapter details the multi-step workflow for hyperspectral and LiDAR data processing, including radiometric correction, image stacking, classification techniques, and terrain analysis using QGIS and ENVI software. Results are presented in the form of thematic maps and

spatial analyses, including paleoriverbed mapping, followed by a discussion that interprets these outcomes. The thesis concludes with a validation of results using ARPAV data, emphasizing the methodological contributions and practical applications for land management and environmental assessment (*Offerta_tecnica_ETRA_DEF*, 2021.; *REPORT VRB/IPERLAND*, 2024.).

GEOLOGY AND HYDROGEOLOGY OF THE VENETO PLAIN

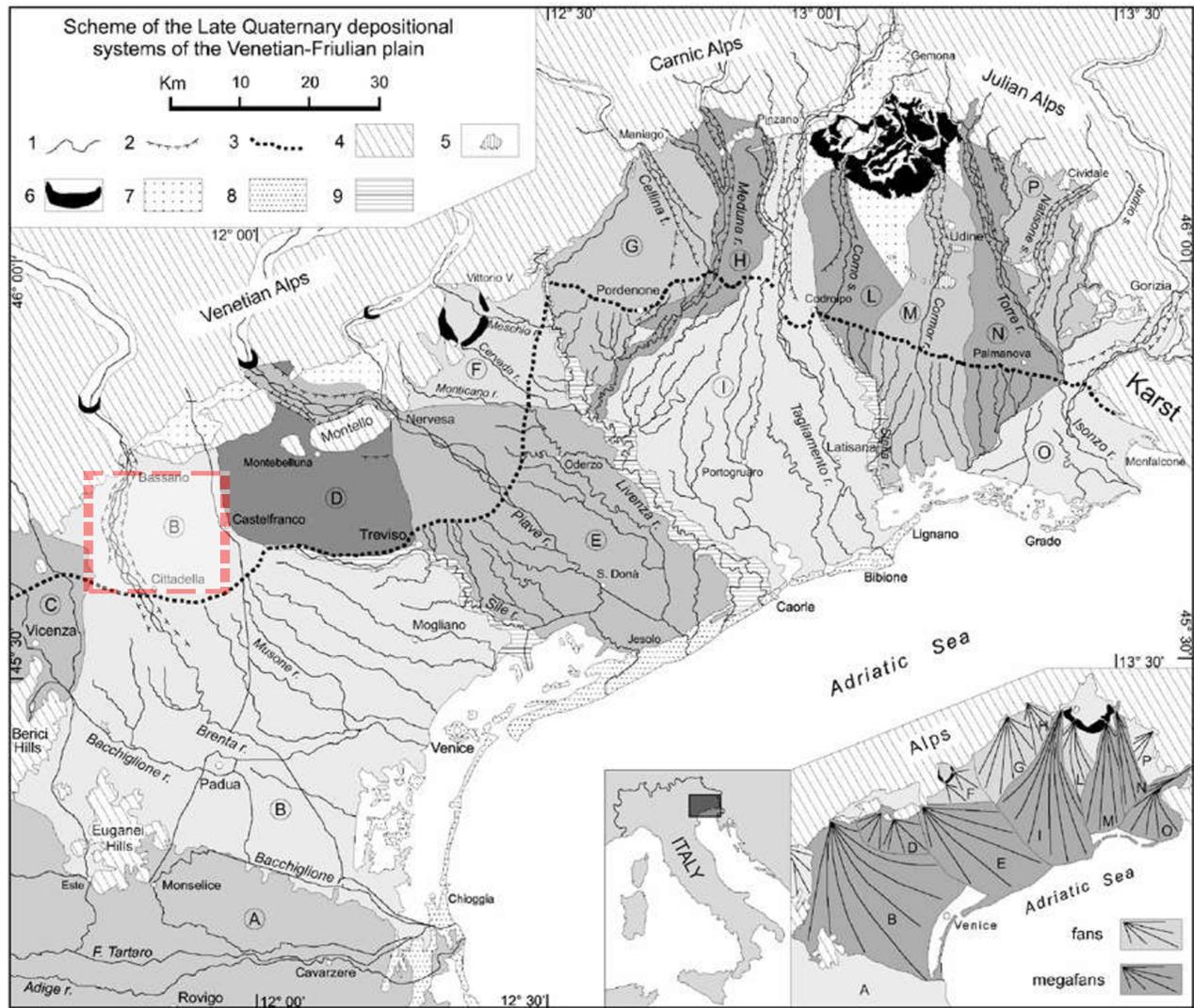## 2.1 Geological & geomorphological framework of the Veneto plain

Figure. 2. Scheme of the Late Quaternary depositional systems of the Venetian–Friulian Plain from (Fontana et al., 2008). In the down-right corner, a simplified sketch of the alluvial megafans and fans is shown. Symbols: (1) river, (2) fluvial scarp, (3) upper limit of the spring belt, (4) mountains and hills, (5) tectonic terraces, (6) end moraines systems, (7) interfan and intermontane deposits, (8) coastal-deltaic systems and (9) groundwater-fed river systems. Grey-tone areas: (A) Adige Alluvial Plain, (B) Brenta megafan, where the red-dashed square highlights the location of the study area, (C) Astico fan, (D) Montebelluna megafan, (E) Piave megafan, (F) Monticano–Cervada–Meschio fan, (G) Cellina fan, (H) Meduna fan, (I) Tagliamento megafan, (L) Corno fan, (M) Cormor megafan, (N) Torre megafan, (O) Isonzo megafan and (P) Natisone fan.

In general, alluvial plains evolve through aggradation, erosion, and deposition, with meandering rivers producing diverse morpho-sedimentary elements (e.g., point bars, levees, crevasse splays, oxbow lakes). Over long timescales, avulsions and compactional processes lead to the development of microreliefs that act as preferential pathways or barriers for channel migration. While river responses to tectonic movements and avulsions have been widely studied, the interaction between rivers and relict floodplain morphologies still remains underexplored (Fontana, Mozzi and Bondesan, 2010; Bellizia et al., 2023).

The Venetian Plain, forming the southern sector of the broader Venetian–Friulian Plain within the Po Plain and Adriatic foreland basin, is bounded by the Southern Alps to the north and the Northern Apennines to the south. It consists of a 700 m-thick sedimentary succession deposited over the past 2.5 My, recording key climatic and sea-level changes. During the Last Glacial Maximum LGM (30–17 ka BP), the Adriatic shoreline shifted 400 km seaward, exposing the plain to substantial fluvio-glacial input that generated thick alluvial deposits (25–30 m). After a sedimentation hiatus of 7–10 ky, late Holocene transgressive–regressive cycles led to the accumulation of fluvial-channel belt deposits under highstand-aggradational conditions. Human modifications became significant during the Roman period (2–1.7 ka BP) with the construction of roads, canals, and agricultural fields, and were dramatically intensified in the 15th century under the Venetian Republic through river diversions, dike construction, and artificial canals. From the 18th century onwards, river lateral mobility was constrained by artificial confinement, while the 20th century reclamation projects transformed coastal swamps and lagoons into agricultural land. The plain is also affected by subsidence, driven primarily by Holocene sediment compaction and tectonic activity, but significantly accelerated by anthropogenic factors such as groundwater withdrawal, with rates reaching up to 10 mm/yr (Teatini et al., 2011). Present-day coastal dynamics reflect a microtidal regime with an average tidal range of ~0.9 m (Fontana et al., 2008).

The Veneto plain, a sector of the Po Valley bounded by the Alpine foothills, Adriatic Sea, Tagliamento, and Po rivers, originated from late Tertiary uplift and foreland subsidence, followed by Quaternary infilling of the depression with alternating fluvial and marine deposits driven by glacial–interglacial cycles. Its floodplain morphology has been shaped by frequent river course changes, forming extensive alluvial megafans downstream of mountain outlets. Structurally, the area is influenced by NO–SE transcurrent faults of the Scledense System, which create a stepped Quaternary basement with variable depths increasing southward (Boscolo and Mion, 2008).

Using remote sensing, sedimentological, and geophysical analyses, it can be examined (i) the longitudinal profile, (ii) the morphometry of paleo-meander bends, and (iii) sediment properties of the channel belt in Veneto region. Results highlight that microreliefs created by contrasting fine- and coarse-grained deposits significantly influenced meander belt evolution, conditioning channel migration, avulsion pathways, and bend morphology. As a result, this demonstrates the critical role of inherited morpho-sedimentary heterogeneities in shaping floodplain dynamics (Bellizia et al., 2023).

The study area between the Astico and Brenta basins lies within the Veneto proximal plain, part of the wider Venetian–Friulian Plain in northeastern Italy. Geologically, it represents the foreland basin of the Southern Alps, progressively filled during the Quaternary by thick successions of fluvial, glacial, and fluvioglacial deposits. These sediments, mainly derived from limestone- and dolomite-rich catchments in the Prealps, form extensive alluvial fans and megafans and are composed of gravelly deposits at their apices that grade downstream into finer silty and clayey sediments.

From the point of view of geomorphology, the study area has been formed by the activity of major rivers (Astico, Brenta, and nearby Piave), which during the Late Pleistocene and Holocene underwent repeated avulsions and channel shifts, leading to leaving behind a dense network of paleo-riverbeds, abandoned channels, and relict alluvial ridges. The plain is divided into a high plain near the Prealps, dominated by coarse gravel fans, and a low plain toward the Adriatic Sea, where finer deposits prevail. Transitional spring zones (Fontanili) occur in the middle plain, marking the shift from unconfined to multi-layered confined aquifers.

As a result, this geological–geomorphological framework makes the area ideal for geospatial and hyperspectral studies aimed at distinguishing soil units and reconstructing paleo-fluvial dynamics. (Fontana, Mozzi and Bondesan, 2010)

2.2 Hydrogeology of the Venetian plain

The Venetian Plain, located in the eastern Southern Alps foreland basin, developed large alluvial megafans from the Brenta and Piave rivers during the Late Quaternary. Their limestone- and dolomite-rich catchments supplied large amounts of clastic debris forming hundred meters of thick gravel deposits in the piedmont high plain, which gradually transit toward the Adriatic into fine-grained alluvial and marine sediments of the low plain. This geological setting has created two major hydrogeological

systems: 1. an extensive unconfined aquifer in the high plain and 2. a multilayered confined to semi-confined aquifer in the low plain. Between these two units lies the middle plain, a 2–5 km wide transition zone where gravelly deposits grade into alternating permeable and impermeable layers, causing groundwater to emerge at the surface as numerous springs known as Fontanili (Fabbri and Pola, 2017).

The Venetian Plain formed through the progressive infilling of the Tertiary foreland depression, mainly with Quaternary continental deposits of fluvial, glacial, fluvioglacial, and deltaic origin. These deposits, largely derived from the Adige, Leogra, Astico, Brenta, and Piave rivers, produced extensive alluvial fans that dominate the hydrogeological and stratigraphic framework of the plain. Fed by glacial melting and moraine erosion, rivers deposited coarse gravels at the outlets of the plain, which gradually graded downstream into finer silty–clayey sediments and formed large megafans that ultimately merged with marine deposits of the coastal low plain. While in the Lombardy sector fans coalesce into an indistinct plain, in the Venetian–Friulian sector, to the east of the Brenta, river-built fans formed by the various rivers remain morphologically distinguishable up to the present coastline. Each river generated overlapping and laterally merging fan systems with variable extents depending on hydrological regimes. In the north of Italy, the term "fan" can be applied to depositional elements limited to the piedmont area (for example in the case of the Astico alluvial fan), while megafans can also be buried structures such as the Piave di Montebelluna system, which constitutes the outcropping part of a megafan whose distal portion is buried. Notable systems include the Tagliamento, Meduna, Monticano–Cervada–Meschio, Piave (Nervesa and Montebelluna), Brenta (Bassano), Astico, and Adige. Some of these, like the Piave di Montebelluna, represent partially buried megafans, illustrating the long-term interplay of river dynamics, sediment supply, and marine transgressions–regressions in shaping the Venetian Plain (Boscolo and Mion 2008).

MATERIAL AND METHODS

3.1 Vector dataset

In order to delimit the study area and obtain information on bare soil only, it was necessary to download some vector data from the Veneto Region Geoportal. Among these, the "Carta dei Suoli" (Soil Map) of the Veneto Region was used as a reference layer for soil unit classification and later comparison with the hyperspectral-derived products. In addition, we used the layer "Limiti Amministrativi poligonali dei comuni della Regione Veneto" selecting only the municipalities under the jurisdiction of ETRA the layer "Banca dati della Carta della Copertura del Suolo aggiornamento 2023" for the provinces of Vicenza, Padua, and Treviso, used to create masks, and the layer "Edifici" for the same provinces, used to integrate buildings not mapped in the previous layer into the masks, particularly those on land considered for agricultural use. Finally, a vector dataset provided by the Department of Geosciences was used to mask the different rasters one by one and cut them in an orderly manner.
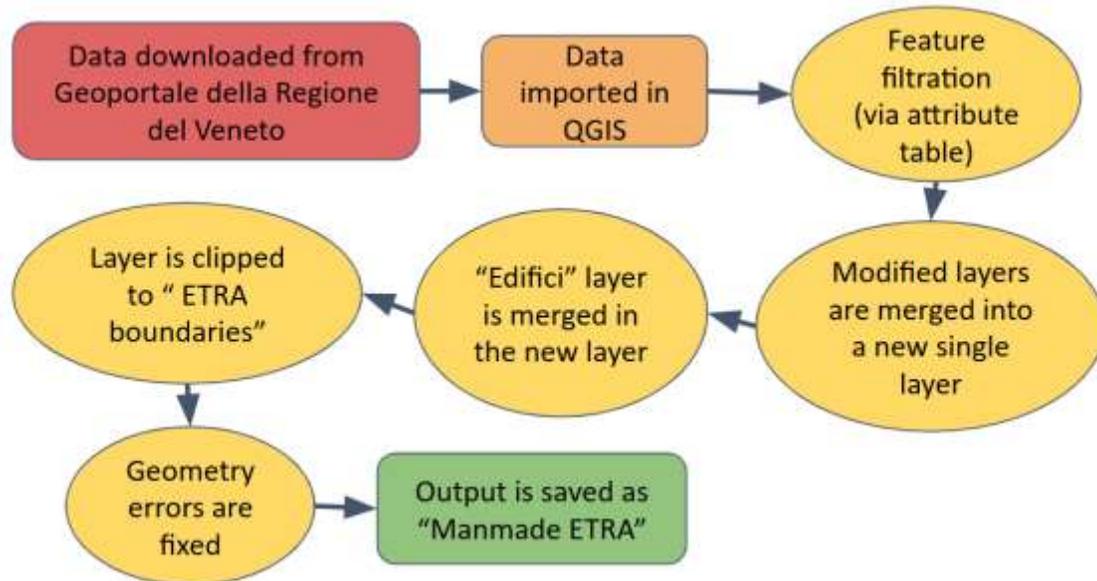
3.2 Raster dataset

Essential to the development of this thesis was the hyperspectral dataset provided by ETRA, acquired using Hyspex VNIR-1800 and Hyspex SWIR-384 sensors mounted on an aircraft between April and June 2022 and consisting of more than 150 images with a resolution of 0.5 m in the VNIR and 2 m in the SWIR; the images were already orthorectified and co-aligned with each other. In the study area covered by this thesis, 39 of these images were processed, all oriented north-south to reduce lighting differences.

ETRA also provided a DEM raster of their entire area of expertise with 1x1 m cells, generated from LiDAR acquisitions made in conjunction with hyperspectral flights. These acquisitions, with a density of 1.5 pt/m², horizontal error of 0.2 m, and vertical error of 0.15 m, made it possible to obtain a high-quality digital terrain model.

A false color RGB raster derived by hyperspectral indices as an output of the workflow that will be described soon, was used as a complement the topographic analysis. This output enhanced spectral information, highlighting soil and sediment composition variations. Importantly, this false color RGB raster was employed only as a visual aid to detect compositional differences, and not as the final soil mapping layer.

3.3 Vectors processing

QGIS software was used for spatial analysis, vector/raster processing and visualization, and then for layer styling, geoprocessing, and map production. Following that, plugins and QGIS extensions (e.g., Mappy, Processing, QuickMapServices) were used for data processing and analysis. This study involved a structured geospatial data processing workflow to obtain information on the study area (Fig.

3).

Figure 3. Workflow designed for generating the "Manmade ETRA" layer

In particular the layer "Limiti amministrativi poligonali dei comuni della Regione Veneto" was used to confine ETRA municipalities by selecting its municipalities within the study area and exporting them as a new layer called "ETRA boundaries". The layer "Banca dati della Carta della Copertura del Suolo aggiornamento 2023" of the three provinces was processed importing the shapefiles into QGIS then by editing the attribute tables, features representing urban areas, permanent green areas and water bodies were selected, while temporary vegetated and agricultural areas, as well as lands without vegetation were deleted. The filtered layers from each province were merged into a single shapefile using the QGIS "Merge Vector Layers" tool. This consolidated dataset represented the key land cover categories to be masked across the three regions. The merged land cover layer was temporarily joined with the "Edifici" layer, to enable spatial comparison and overlay. This step was performed as a preparatory operation for subsequent clipping process through the "ETRA boundaries" layer, allowing for spatial delimitation.

After the merging process, 137 geometric errors were identified within the dataset. These included issues such as invalid polygons, overlapping features, and topological inconsistencies. The "Check Geometry Validity" and "Fix Geometries" tools in QGIS were used to correct these errors, ensuring spatial integrity for further geoprocessing tasks.
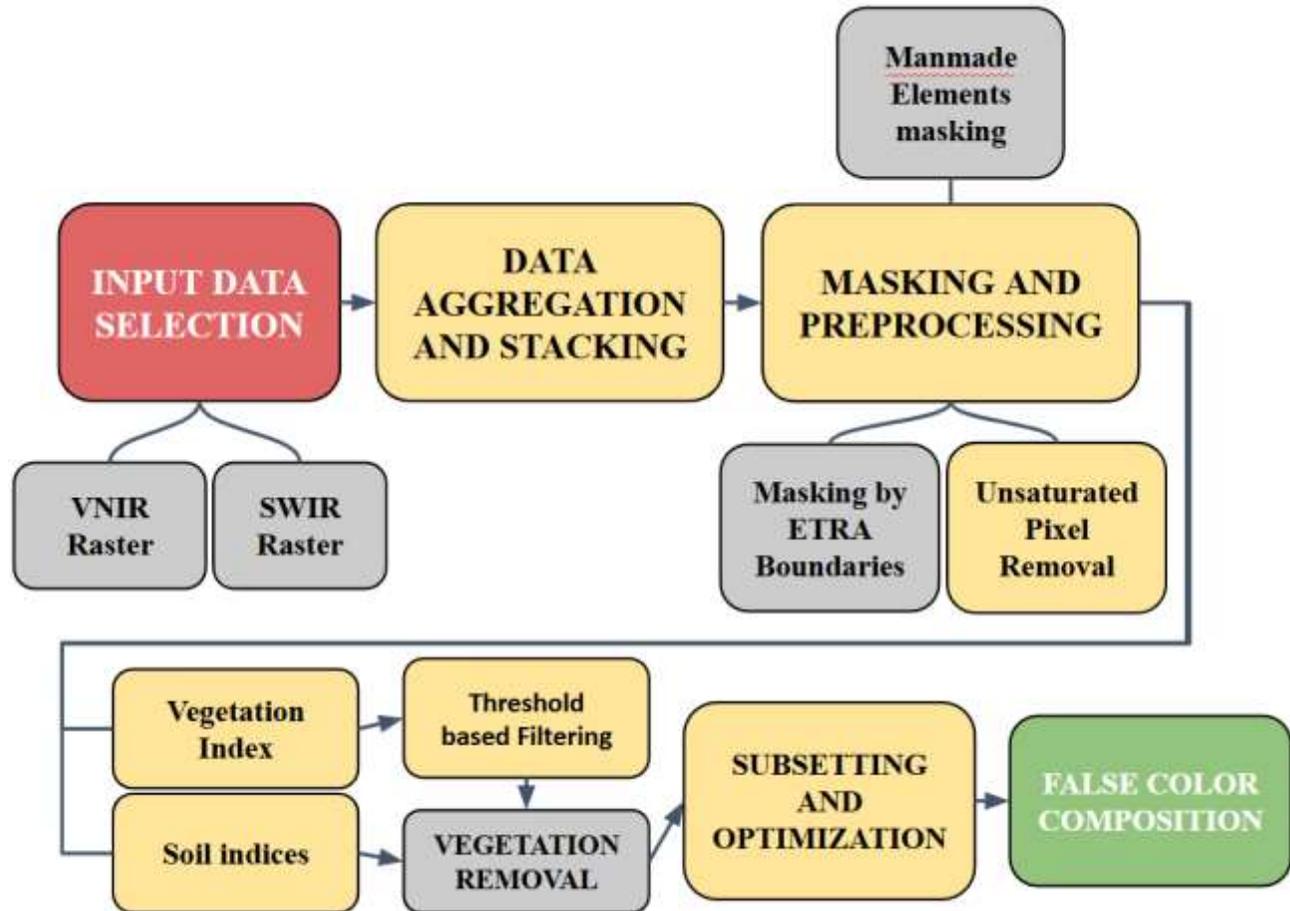
3.4 Hyperspectral Image Processing using ENVI

Figure 4. Workflow of hyperspectral data pre-processing, masking and classification

ENVI (Environment for Visualizing Images) is a specialized remote sensing software widely used for processing and analyzing hyperspectral and multispectral data. In this thesis, ENVI was employed to preprocess and classify VNIR and SWIR hyperspectral images, including stacking, masking, index calculation, and semi-automated soil classification. Its tools allowed for the extraction of spectral information, the removal of non-soil elements such as vegetation and urban features, and the generation of input layers that were later integrated with QGIS for cartographic representation (Jia et al., 2017; Kaba and Leloglu, 2023). Hyperspectral remote sensing provides high-resolution spectral data, enabling

precise land cover classification and soil analysis. In particular it enables detailed analysis of surface materials based on their spectral reflectance properties. Unlike traditional multispectral imaging, hyperspectral sensors can capture data across hundreds of contiguous bands, allowing for highly accurate material identification. Soil classification requires precise spectral information, which can be affected by various factors such as vegetation cover, urban structures, and atmospheric conditions. The presence of vegetation can obscure soil signals, while human-made features such as roads and buildings make additional spectral noise. This study applies a hybrid approach as a structured workflow (Figure 4) for processing hyperspectral imagery using VNIR and SWIR bands to generate soil indices while removing vegetation and manmade elements (Tab 2). The workflow involves multiple stages, including data pre-processing, raster aggregation, image masking, and final optimization through region-based subsetting. By systematically filtering out spectral noise and non-soil elements, this approach ensures higher classification accuracy and reliability in soil mapping and analysis.

Data preparation

The workflow begins with the selection of VNIR and SWIR image pairs, which are spectrally subsetted at 960 nm to allow a correct layer stacking. Images can now be virtually aggregated into a VNIR+SWIR Stack, combining spectral information from both rasters.
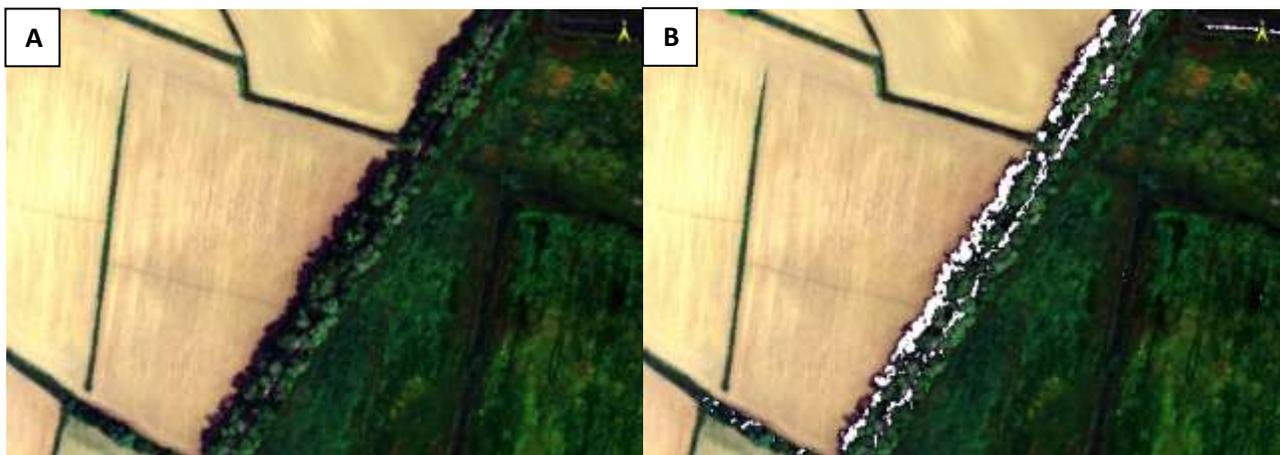

Figure 5. Unsaturated pixel removal effect on shaded regions: before (A) and after (B)

In the stacking process output pixel size was set to 2 m. Following data aggregation, the stacked raster underwent a series of masking and thresholding operations to refine the dataset as following:

- Masking by "ETRA Boundaries": The raster was masked to ensure that the analysis focused only on relevant areas (Fig. 6b).
- Unsaturated Pixel Removal: A band in the green region (546nm) of the spectrum was selected, and a threshold was also applied to remove low reflectance values of pixels (reflectance below 0.015). These pixels typically corresponded to shaded regions (Fig. 5), water surfaces, or sensor noise, which could otherwise create errors while calculating soil indices. The band was selected since it's more representative for this purpose.

Figure 6. Virtual steps of the workflow before the actual output: layer stacked and the ETRA boundaries" vector (A), the same layer cutted by the boundaries (B); finally the layer filtered of the unsaturated pixels (C).

Feature Extraction

After pre-processing the dataset, spectral indices were applied to extract soil information while filtering out non-soil components. In particular we proceed as follows:

- Vegetation Index Calculation: A spectral vegetation index (Modified Soil Adjusted Vegetation Index 2 - MSAVI2) was computed to identify (Fig 7b) and later remove vegetative cover from the images. Reflectance delta between the strong absorption in the red spectrum and high reflectance in the near-infrared spectrum allowed efficient vegetation differentiation.

- Soil Indices: several indices were calculated (Fig 7a) to highlight soil mineralogy and textural differences. In particular indices for clay content (Clay Alteration Index), carbonates (Calcite Index) content and crop residues (Cellulose Absorption Index) were calculated.

Table 1. Indices used to process hyperspectral data

MSAVI2	$(2 * NIR + 1 - \sqrt{((2 * NIR + 1)^2 - 8(NIR - Red)))}/2$	(Qi et al., 1994)
CALI	$(r2205/r2330) * (r2395/r2330)$	(Ninomiya, 2004)
CAI	$0.5 * (r2000 - r2200) - r2100$	(Daughtry, 2001)
CLAI	$(r1650 + r2205) / r2165$	(Rowan and Mars, 2003)

Vegetation and "manmade" elements removal

Then, additional filtering as the next step was performed to refine the dataset (Fig 7):

- removal of "manmade" elements: land elements such as roads, rooftops, industrial areas and water bodies were identified and masked out (Fig 7c);
- threshold-based filtering: a thresholding to MSAVI2 index was identified (values higher than 0.05) and applied to select land cover by vegetation, creating a binary mask;
- vegetation masking: vegetation is masked from the soil index raster to remove spectral interference of plant cover (Fig 7d).

Final subsetting and Optimization

The last step in the workflow involved optimizing the processed raster by subsetting them with the layer provided by the Geoscience Department, specifically created to reduce the final file size and achieve a more accurate output mosaic. The final output for each stacked image is now a three-band false color RGB image where R band is the CLAI index (clays), G band is the CALI index (crop residues) and the B band is the CAI index (carbonates). For a better visualization "Equalization" stretching is applied and then an overall mosaic of the study area is exported in TIFF format.
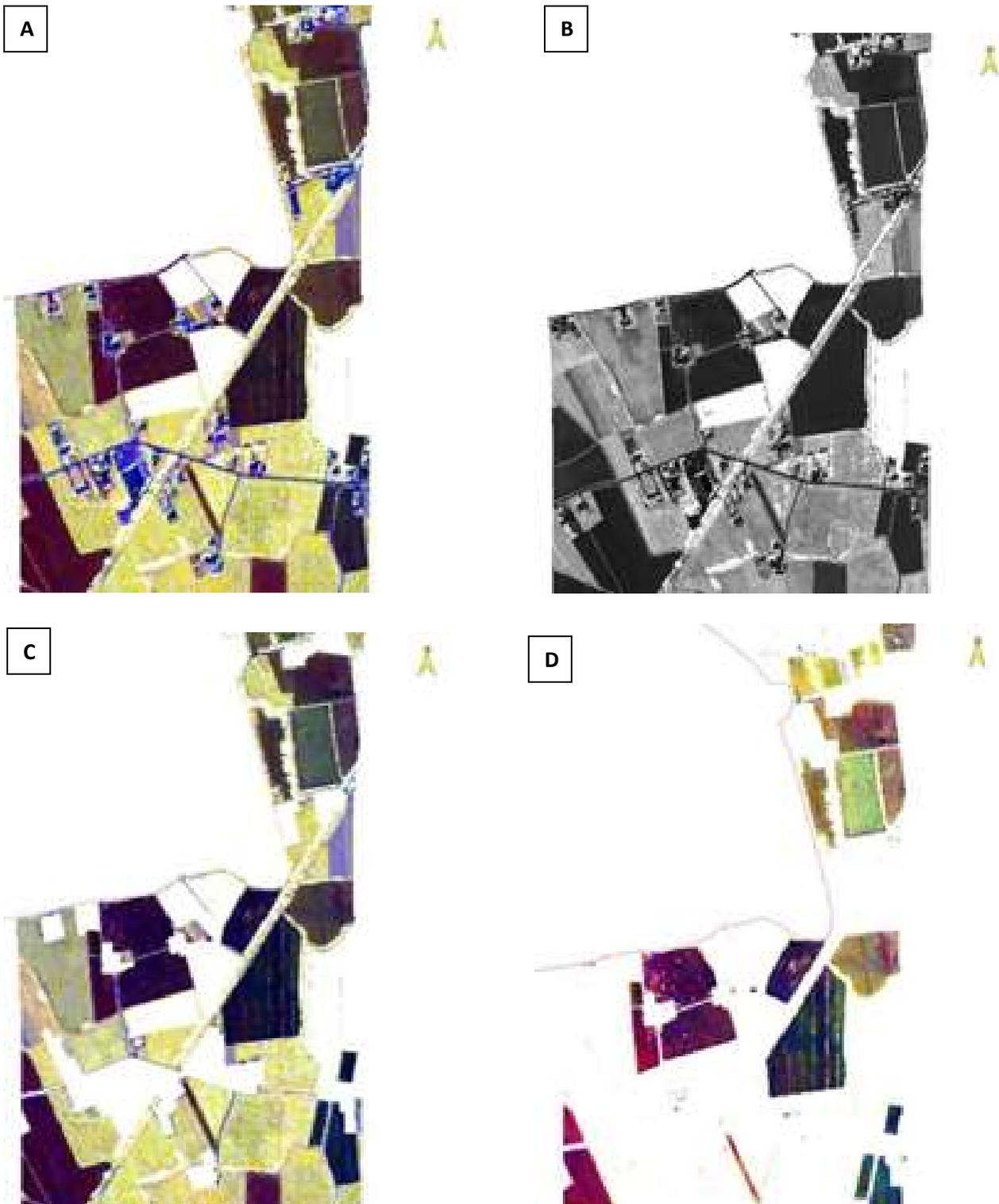
Figure 7. Here the last virtual steps are shown, before the final output: soil indexes are computed (A) in the image already preprocessed, while in parallel to this MSAVI2 (B) is computed to then remove vegetation. "Man made" elements are removed from the index layer (C) and so vegetation (D), to leave only bare soil areas.

3.5. QGIS mapping
Soil Mapping

Soil mapping involved spatial representation of different soil types based on their properties, composition, and distribution. QGIS Mappy Plugin provided an efficient workflow for digitalizing soil types through polygon-based mapping allowing the production of detailed thematic maps. The integration of DEM-derived terrain features and spectral indices further refined soil classifications, improving overall accuracy and applicability.
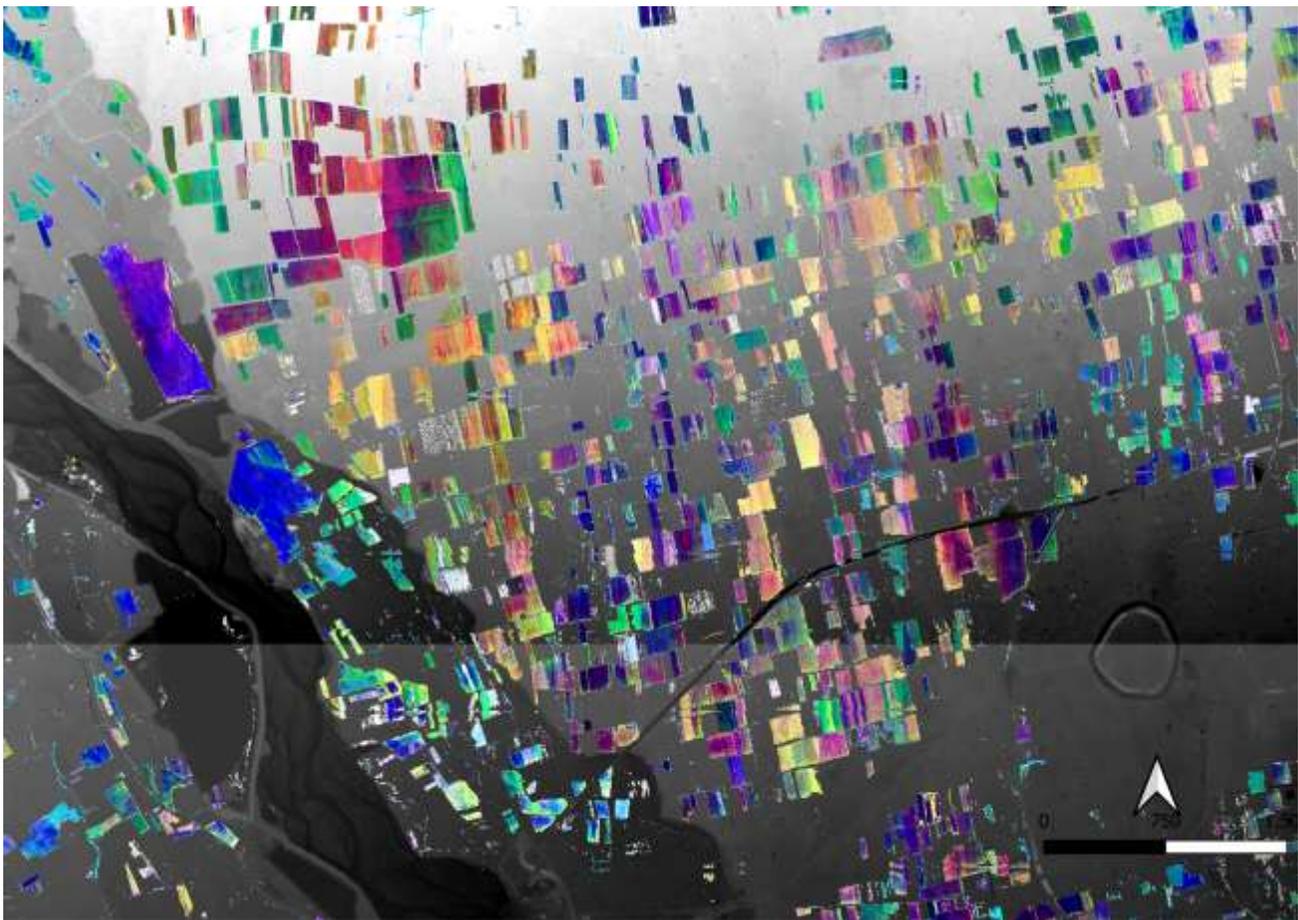

Figure 8. When the false color RGB raster and DEM are overlaid the relationship between elevation and mineralogy is immediately noticeable.

Once the DEM and RGB raster layers are imported (Fig 8), the next step is polygon digitization. In Mappy, a new vector layer is created to represent soil units. Then distinct soil boundaries are manually digitalized keeping a visual scale from 1:1000 to 1:2500 using the polygon drawing tool, based on visual interpretation of imagery or by the aid of ARPAV "Carta dei Suoli". Each digitized polygon corresponds

to a unique soil type, based on color and tone, which is critical for accurate mapping. After the polygons are created, attributes such as soil type, texture, and classification codes are assigned to the polygons. These attributes are important for linking the spatial data to real-world soil characteristics and facilitating further analysis.

Mapping of soil types in Mappy is done through a color-based system. Once the polygons are digitized, a color scheme is applied to represent different soil types, allowing for easy differentiation between them. For example, sandy loam might be represented in yellow, clay loam in red, and silt clay loam in purple. Additional adjustments are made to the symbology, such as altering the transparency of the polygons or adjusting border thickness and also modifying polygons by vertex tools for better visual clarity. Once the soil map is generated, it is finalized by adding important map elements such as a legend, scale bar, north arrow and title.

Paleochannel and riverbank mapping

The mapping approach was designed to integrate topographic (DEM) and spectral (RGB raster) data to enhance the detection of paleochannels and riverbeds. The methodology followed a multi-step GIS-based workflow, ensuring precise classification and visualization of fluvial features. The workflow encompassed data acquisition, preprocessing, analysis, and final map generation.

Mapping process began by importing DEM data, which provided crucial insights into terrain morphology, helping distinguishing between old, buried channels and surrounding terrain and the false color RGB raster, which enabled detecting soil and sediment composition variations that indicate past water flow due to their unique mineralogical signatures. By overlaying DEM and the false color RGB raster in QGIS, a multi-dimensional view of paleochannels and riverbeds, these features were extracted by visually interpreting subtle topographic depressions and linear geomorphic patterns that suggest the presence of ancient fluvial channels. In particular DEM symbology was modified by selecting a stretching of "mean +/- standard deviation" multiplied by a factor of 2 and statistical extent was set to "Updated canvas" to better enhance elevation differences. Visual scale was kept from 1:1000 to 1:5000 to achieve greater accuracy and mapping resolution. Following this visual processing, as for soils, the final step involved cartographic representation of the detected paleochannels and riverbanks using Mappy. Finally, the soil, paleochannel, and riverbed maps were created with scale bar, north arrow, and legend and then exported.

RESULTS

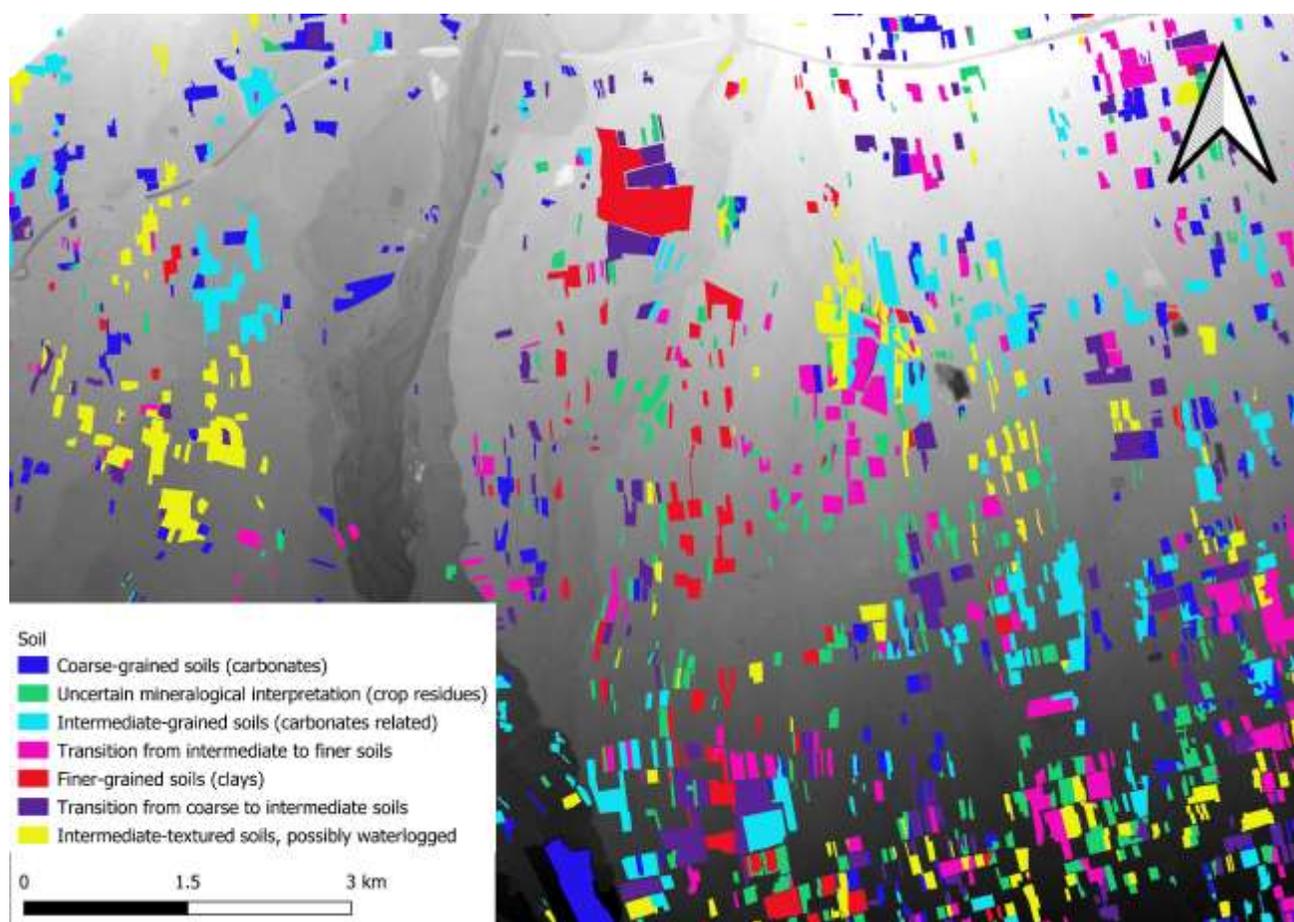## 4.1 Maps and legend shaping

Fig 9. Individual bare soil units are mapped interpreting the false colour RGB rasters.

The soil map produced in this study (Fig. 9 and 10) integrated hyperspectral derived and geomorphological datasets to delineate seven distinct soil units across the ETRA service area, located between the Brenta and Bacchiglione rivers. Each class reflects a unique combination of textural, mineralogical, and hydrological characteristics, closely associated with the geomorphic framework of the region. The legend follows a color-coded scheme (Tab. 2) that ensures visual clarity while preserving thematic consistency with ARPAV's regional soil maps. Color continuity and adjacency logic were applied to prevent eventual abrupt transitions between different false color RGB images where natural geomorphological boundaries were gradual. Units were not only colored based on visual cues but

Table 2. Color-coded scheme used for soil mapping in the study area.

Color	Interpretation
	Coarse-grained soils (carbonates)
	Transition from coarse to intermediate soils
	Transition from intermediate to finer soils
	Finer-grained soils (clays)
	Intermediate-textured soils, possibly waterlogged
	Uncertain mineralogical interpretation (crop residues)
	Intermediate-grained soils (carbonates related)

interpreted in the context of surrounding units and DEM elevation, starting from the assumption that RGB bands are respectively related to clay index, crop residues index and carbonate index.

Since blue and light blue units can be found generally at a closer distance from the Brenta river bed, we interpreted them as soils with higher carbonates content, belonging to the recent holocene, and might be typically associated with former riverbeds, levees, or raised fluvial deposits. Violet and purple classes, intended as shades of blue and red respectively, can be often found: violet, in transition zones between coarse riverine deposits and finer floodplain materials, purple might represent depositional environments with reduced current strength. Based on the index, red is related to clays and was interpreted as finer-grained/textured soil, while instead yellow as an intermediate textured whose units can typically be found in areas where we suspect poor natural drainage, both due to their natural position and also by assessing it in true color images. Lastly, green parts remain of difficult interpretation since they could eventually represent actual crop residues but seeing their abundance on the map that is unlikely, they might instead represent an intermediate soil class between intermediate and finer textured soils.
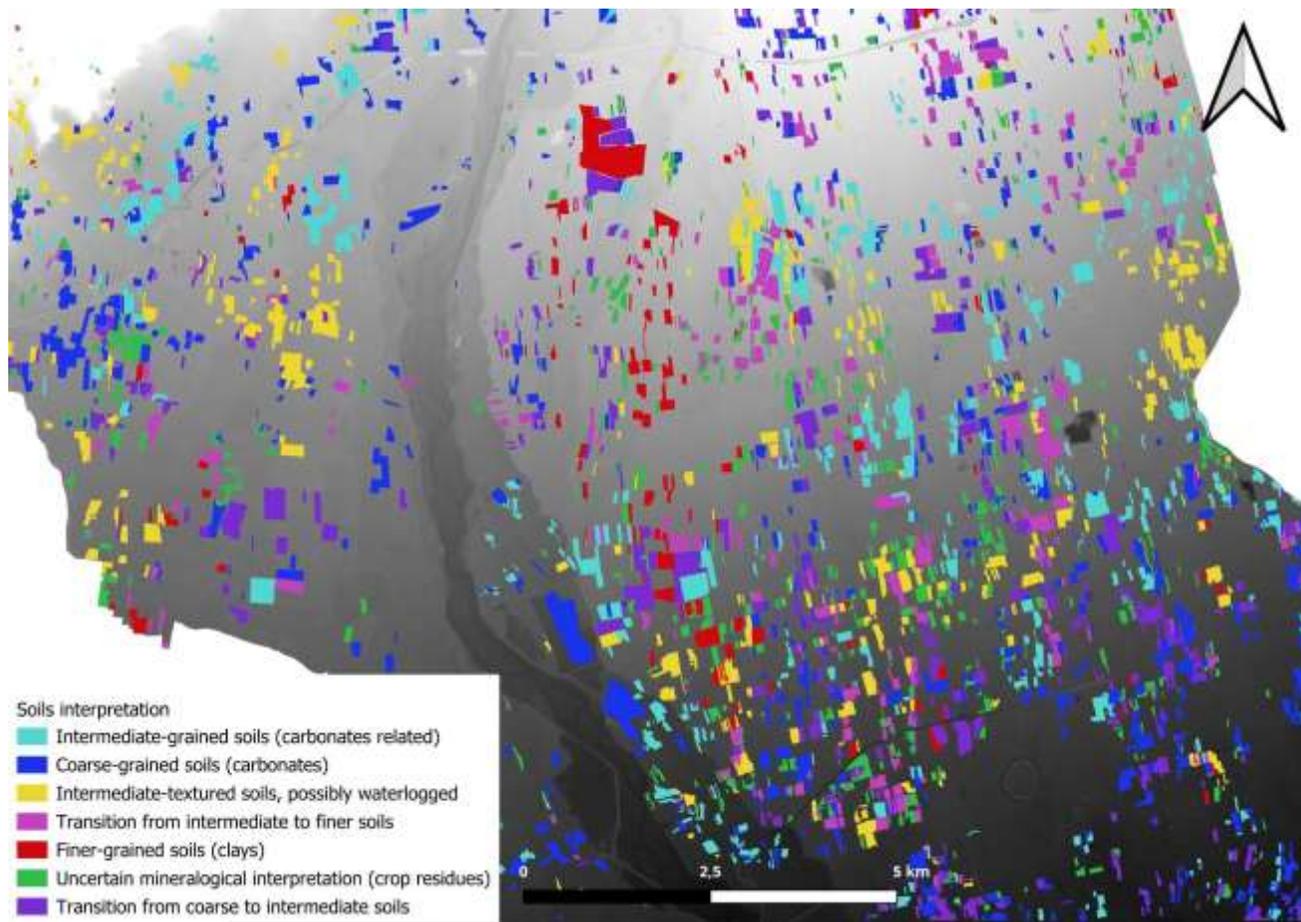
Figure 10. Overall soil mapping of the study area.

In addition, paleorivers were identified through subtle topographic depressions in LiDAR-derived DEM, combined with indices indicators of coarser sediment (carbonates). These features often appear as broad, sinuous traces aligned with coarse-grained alluvial soils and their distribution reveals multiple phases of Brenta River migration and avulsion, corresponding to active or recently abandoned channels with higher energy flow regimes. These are associated with sedimentation, predominantly sandy–gravelly deposits, and areas of high permeability.
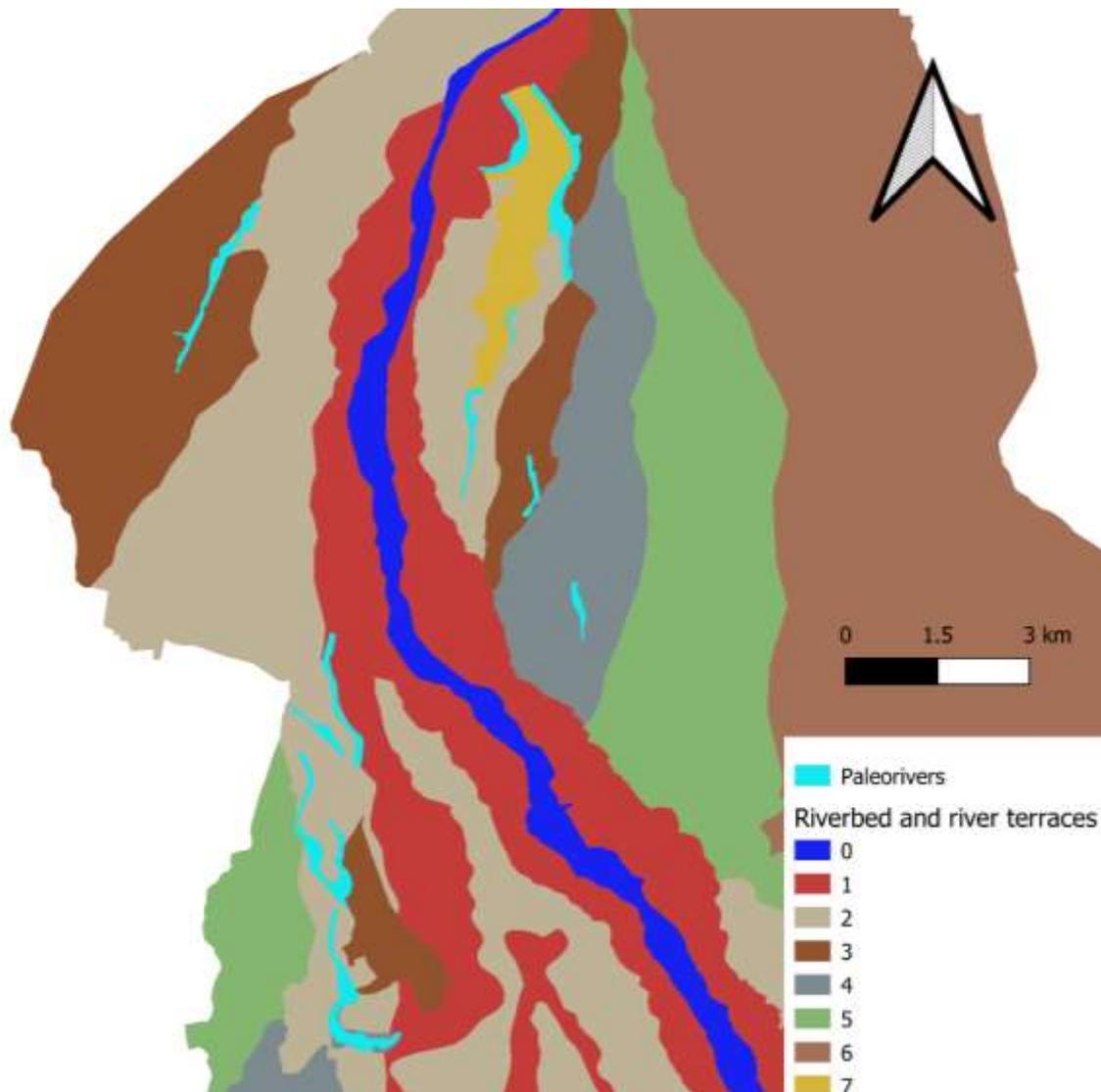
Fig 11. Map highlighting river bed and terraces, as well as palorivers.

In the bedriver classification map, the Brenta River itself was coded as class 0, while the surrounding units were grouped into classes from 1 to 7 according to their progressive distance from the Brenta River (class 0). Units closer to the river channel generally show stronger geomorphological and hydrological connections, such as active or recently abandoned paleochannels, floodplain depressions, or areas with higher susceptibility to flooding and sediment input. As the distance from the Brenta increases, these influences gradually weaken, and the mapped classes correspond more to relict geomorphic features, reclaimed soils, or anthropogenic surfaces with less direct hydraulic connectivity to the river. This dual

perspective—elevation and distance—provides a more comprehensive understanding of how the Brenta River interacts with its surrounding floodplain (Hajek and Wolinsky 2012; Lewin and Ashworth 2014).
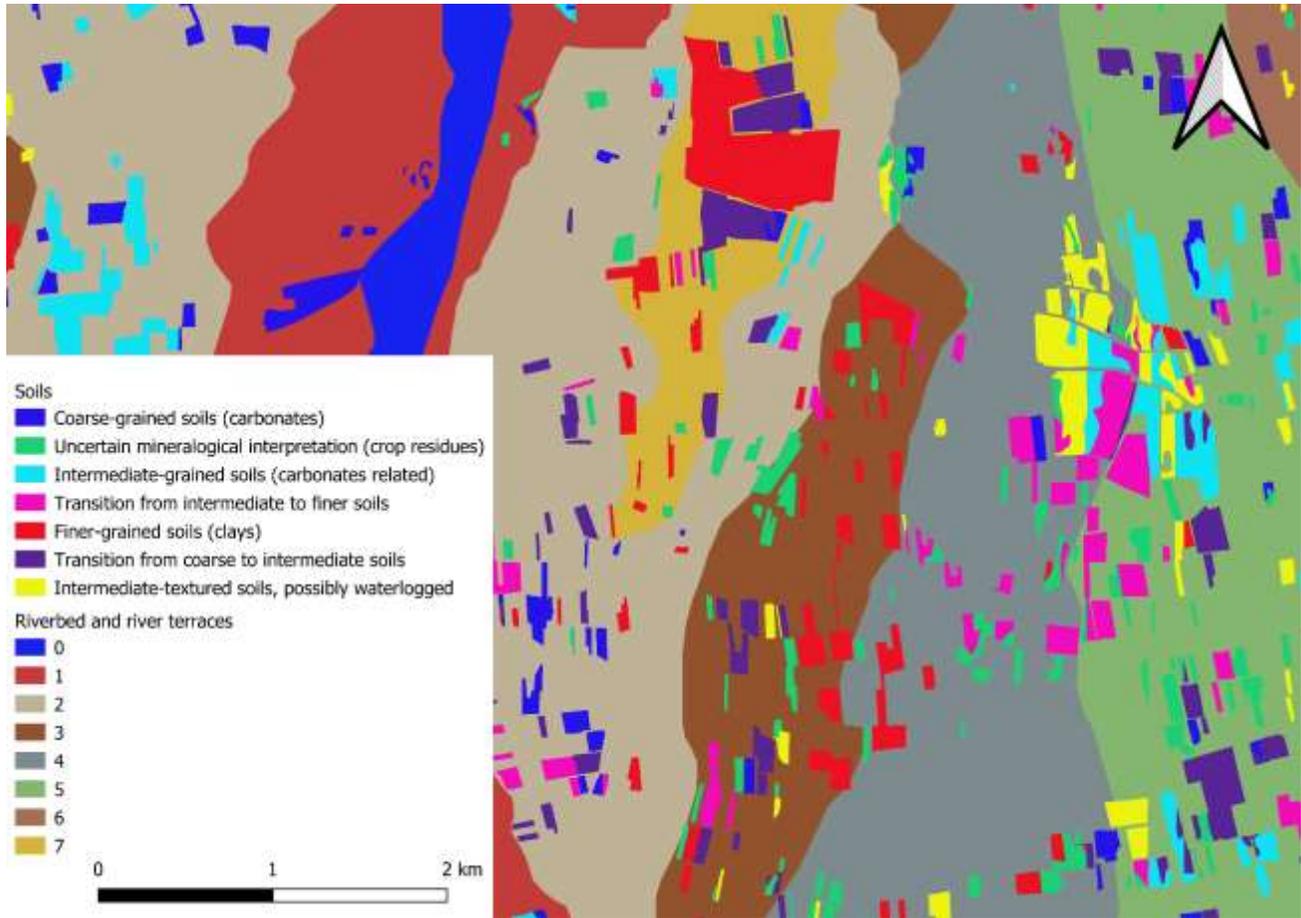

Figure 12. In general, along the same river terraces soils unit identified show a certain spatial correlation.

This mapping provides a detailed and thematically rich interpretation of the soil cover, significantly improving upon the generalised boundaries of existing regional maps. The spatial distribution of these units somehow reveals relationships with the paleo-hydrological history of the region (Fig. 12). Coarse alluvial deposits are concentrated along riverbed traces, while fine-textured and hydromorphic units dominate interfluve depressions. As an example, in figure 12 is shown the terrace occupied by Cartigliano municipality (in the legend 7 and 2), historically known to belong to the last glacial maximum period (Mozzi, 2005), where soils seem to be more fine-grained and similar between each other and form a sort of cluster, a behavior anyhow displayed also in the other terraces.

DISCUSSION AND CONCLUSION

The integration of hyperspectral and LiDAR datasets within the IPERLAND framework has not only refined the spatial resolution of soil classification in the ETRA territory but has also revealed the enduring influence of paleo-hydrological processes on present-day soil patterns. By explicitly incorporating paleoriver and bedriver mapping into the mapping workflow, this study has addressed a gap in traditional soil surveys which have the tendency to focus exclusively on modern hydrological networks while neglecting the paleo-geomorphic of fluvial dynamics.

The Brenta River, together with its paleochannels, emerges as a dominant agent in shaping soil variability across the study area. Coarse-grained alluvial soils delineated along active and relict channels reflect high-energy depositional environments, while the fine-textured and hydromorphic units occupying interfluve depressions represent low-energy zones with longer water residence times. This spatial arrangement is not coincidental, as it reflects centuries of channel migration, avulsion, and sediment sorting. These insights not only confirm the strong geomorphic control on soil genesis but also highlight the importance of historical landscape reconstruction in modern soil interpretation.

From a methodological standpoint, the semi-automated ENVI–QGIS workflow demonstrated its robustness in combining multi-source datasets into a coherent mapping scheme. The targeted masking of vegetation and urban areas ensured that spectral analysis was applied exclusively to exposed soils, which was essential in mapping workflow. Soil spectral response is highly sensitive to moisture, organic matter, and mineralogical composition, but these signals can easily be obscured by vegetation canopies or artificial surfaces. Vegetation strongly absorbs in the visible red and reflects in the near-infrared, while manmade areas often show reflectance patterns that can overlap with bright soils, such as sandy or calcareous units (Ben-Dor et al., 2009; Mulder et al., 2011). If these features are not removed, they introduce significant spectral mixing and misclassification errors, particularly in transitional environments where land cover is heterogeneous (Demattê et al., 2018). By applying a vegetation index to detect and exclude green biomass, and by masking anthropogenic features using ancillary land-use data, the workflow isolated almost only pure soil pixels. This ensured that the classification algorithm exploited the true soil spectral response rather than composite signals influenced by surface cover. Similar approaches have been recommended in recent hyperspectral soil studies as a prerequisite for

achieving reliable mineralogical and textural discrimination (Rossel and Behrens, 2010; Thenkabail and Lyon, 2016).

The improvement over the baseline soil map is not only a matter of resolution; it is also thematic, enabling a clearer discrimination of transitional zones and depositional heterogeneity within what were previously mapped as uniform units. These refinements have practical significance in the future studies and scientific approaches. For instance, in agricultural planning, distinguishing between coarse-grained channel deposits and fine-grained overbank sediments can inform crop selection, irrigation scheduling, and soil amendment strategies. In flood risk management, recognising that paleochannel belts are more permeable but less retentive than adjacent clay-rich basins can guide zoning regulations, levee placement, and emergency planning. In ecological restoration, identifying organic-rich and hydromorphic zones can offer potential opportunities for targeted wetland rehabilitation and biodiversity enhancement. The value of this approach thus extends well beyond academic mapping and consequently it directly supports decision-making in resource management, infrastructure development, and climate adaptation. Moreover, the approach could have a high degree of transferability: while the study was conducted in the Veneto plain between the Brenta and Bacchiglione rivers, the workflow can be adapted to other regions where paleofluvial systems and high-resolution remote sensing data are available. This adaptability stems from the workflow's flexibility: LiDAR-derived DEMs capture microtopographic signatures of paleochannels, hyperspectral imagery characterises surface mineralogy while GIS integration enables validation against existing datasets. All together, these components might form a scalable, reproducible methodology that bridges the gap between regional soil surveys and local-scale land management needs.

Building on the results of this study, several avenues for future research and application are recommended:

1. Multi-Temporal Analysis of Soil and Hydrological Change
   - Acquisition, analysis and incorporating multi-temporal hyperspectral and LiDAR datasets to monitor seasonal and interannual changes in soil moisture, vegetation cover, and sediment deposition, particularly in paleochannel zones, particularly within paleochannel belts.
2. Integration with Subsurface Data

- o Combine remote sensing results with borehole logs, geotechnical, and geochemical data and analysis to improve the interpretation of soil genesis and subsurface stratigraphy.

3. Higher-Resolution Hyperspectral Sensors and Imaging
   - o Apply UAV/drone-based hyperspectral sensors and imaging to achieve sub-metre resolution mapping, improving the delineation of transitional soil units and small-scale geomorphic features.

4. Automated Paleochannel Detection
   - o Develop machine learning algorithms capable of automatically detecting and classifying paleochannel features from LiDAR-derived DEMs and multispectral indices.

5. Scenario Modelling for Land Use and Climate Change
   - o Integration the refined soil and paleoriver maps and use them as inputs for hydrological and land suitability models to forecast and assess the potential impacts of climate change, land use change, and extreme flood events.

6. Regional Expansion, Application and Comparative Analysis
   - o Extend and apply the methodology to other alluvial plains within the Veneto region and beyond to assess its robustness and adaptability across different geomorphological and climatic settings.

By pursuing these directions, the potential of hyperspectral–LiDAR integration for soil and paleohydrological studies can be further expanded, ultimately contributing to more resilient and sustainable land and water management strategies in the face of environmental change and geologically and hydrologically complex territories.

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