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Development of a harmonized map of soils and soil hydraulic properties for the Po Plain- Northern Italy

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A B S T R A C T

Study region: Po Plain, Northern Italy

Study focus: Accurate soil hydraulic parameters are essential for the implementation of hydrological models to support water resources planning and management. The availability of spatially extensive and consistent soil hydrological data is important in areas like Po Plain, where intensive irrigation practices and complex hydrological dynamics require reliable data for effective water resource management. Currently, there is no comprehensive, harmonised pedological and hydrogeological database covering the entire Po Plain, while there are independently managed databases at Regional level, often structured differently, which significantly limits their use on a large scale. This study addresses this gap by harmonizing and integrating scattered soil information into a unified and standardized spatial dataset of soil physical and hydraulic properties for the entire Po Plain.

New hydrological insight for the region: The newly developed soil map represents a major advance in spatial resolution, consistency, and regional coverage for the Po Plain. It provides, for the first time, a harmonized and spatially continuous representation of soil types and hydraulic properties across the entire Po Plain. Overall, the map establishes a foundational framework for integrated, evidence-based water resource planning in one of Italy's most hydrologically critical regions. Furthermore, the developed map preserves a comprehensive set of physical and chemical soil attributes, allowing future implementation of alternative Pedotransfer Functions and ensuring flexibility across different research objectives.

1. Introduction

Soil maps are a fundamental tool for understanding the spatial distribution and variability of soils, providing information on key physical and chemical properties, such as texture, organic carbon, pH, nutrient content, and water-holding capacity that influence a wide range of environmental processes and land-use assessments. They are essential for evaluating soil erosion risks, land degradation, and the effects of land-use change (Arrouays et al., 2017). Among their various applications, soil maps are widely used in agricultural planning to support crop selection, fertilization, and irrigation strategies. Information on soil hydraulic properties is particularly valuable, as it is directly employed in agro-hydrological models to simulate soil–water plant interactions and promote sustainable

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water management. In particular, these properties determine water retention, infiltration, and movement through the soil, influencing crop water availability and irrigation efficiency (Wösten et al., 1999).

The characterization of spatial variability of soil hydraulic properties requires extensive sampling to achieve accurate measurements through laboratory or field methods. Although direct measurements can provide highly representative local data, the effort and costs involved make them unsuitable for large-scale assessments (Wösten et al., 2001; Baroni et al., 2010). As a result, many studies have focused on estimating soil hydraulic parameters using indirect methods, such as empirical relationships called Pedotransfer Functions (PTFs), based on more easily accessible soil data, such as texture and organic carbon content. Research over the years has highlighted the challenges in accurately estimating soil hydraulic parameters for hydrological modelling through PTFs. Among them, comparative analyses by Gijsman et al. (2002), Islam et al. (2006), and Nemes et al. (2006) have underlined considerable variability in PTF predictions, affecting both the accuracy and temporal dynamics of simulated soil moisture. However, further works by Baroni et al. (2010) and Wassar et al. (2016), conducted in maize field located in Northern Italy (Landriano – PV), confirmed that, although laboratory methods offer a higher precision, PTFs provide a practical balance between accuracy and feasibility.

PTFs development is supported by an increasing availability of soil properties measurements and the systematic organization of these data into Regional, national and international databases. However, despite these advances, some limitations persist. One of the fundamental challenges in the application of the PTFs lies in the limited availability and quality of essential input data. The input data are either continuous soil information (e.g., sand, silt, clay and organic carbon content, and bulk density) or soil class information (e.g., 12 USDA textural classes) or combination of continuous and class/categorical data (Van Looy et al., 2017). In many cases, the necessary input parameters are either not measured at all or are collected using inconsistent or outdated methodologies, or are available with a sparse spatial coverage (Van Looy et al., 2017).

While global soil databases such as SPADE/M (Hiederer et al., 2006; Arrouays et al., 2017), SoilGrids (Hengl et al., 2017; Poggio et al., 2021), SSURGO (NRCS National Soil Survey Center, 2016) and HWSD (Harmonized World Soil Database; Fischer et al., 2008) offer harmonized, large-scale data to support PTF applications, they often rely on interpolated values from sparse field observations and lack the resolution needed for site-specific applications. On a European scale, many maps and datasets were produced, but with very simplified soil data (e.g. Tóth et al., 2017). In addition, HWSD, despite its widespread adoption, was built upon outdated, heterogeneous source data with a coarse spatial resolution and lacks detailed vertical soil profile information (Poggio et al., 2021).

Recent studies have tried to overcome limitations in soil data availability by integrating machine learning (ML) techniques with global soil datasets. For example, Ali et al. (2025) developed ML-based (PTFs) to estimate spatially distributed soil hydraulic parameters using SoilGrids variables across Great Britain, with the objective of improving water flow simulations for water resources management, planning, and extreme event prediction. While the approach demonstrates potential for wider application, its transferability was assessed in only one additional basin outside the Great Britain, which is the Loire River basin in France, thus limiting evidence of its broader generalizability.

Consequently, the availability of harmonized national and Regional soil maps remains essential for capturing spatial variability and meeting land management needs. In the European Union, for example, national soil maps at a minimum scale of 1:250,000 are recommended (Soil Atlas of Europe, European Soil Bureau Network, European Commission, 2005). They provide a general framework of the main genetic and functional soil characteristics, as well as an overview of the issues related to their use and management, but finer scales (e.g. 1:50,000) are crucial for accurately detecting regional soil variability and supporting effective resource management.

One limitation to the application of PTFs in large-scale studies is that commonly both types of maps and the associated soil profiles are often produced by different agencies, at different times, and using criteria that are not entirely consistent. This is the case in the Po Plain, the largest intensively irrigated plain in Europe, whose territory is divided among several Regions (including almost totally Lombardy, Emilia-Romagna and Piedmont, three of the major Italian Region), each of which acts independently to produce soil maps of their respective territories. Therefore, the current landscape of soil data availability is characterized by a fragmented environment, whereby each Regional authority or environmental agency collects and manages data independently, often using different methodologies, formats, and different international or internal standards. This is even more true for derived soil hydraulic parameters. For instance, in the Lombardy Region, these parameters are derived via PTFs applied to soil data from a 1:250,000 scale soil map and then used in a standardized methodology, adopted by the Regional authority (D.d.s. n.4346/2018; Regione Lombardia, 2018), for estimating irrigation water requirements based on the IdrAgra agro-hydrological model (ANBI Lombardia, 2016-2024). Emilia-Romagna Region conducted extensive field data collection and harmonization, estimating hydraulic parameters through a combination of expert knowledge of the Regional soil characteristics, direct measurements, and tailored PTF applications (Regione Emilia-Romagna (Tarocco, Calzolari, Ungaro) (2021a); Regione Emilia-Romagna (Tarocco, Aprea) (2021b)). Similarly, the Regional Agency for Environmental Prevention and Protection (ARPA) of the Veneto Region estimated available water content (AWC) at a Regional scale using the PTFs developed by CNR-IBIMET to calculate key soil water content parameters (ARPAV Regional Agency for Environmental Prevention and Protection Centro Veneto Suolo e Bonifiche, 2019). At a broader interregional scale, the Italian National System for Environmental Protection (SNPA) compiled 1:250,000 scale soil data from Regional authorities across the Po-Venetian Plain and applied locally adapted PTFs to estimate field capacity, wilting point, and available water content (AWC) (Munafò et al., 2021). These varied approaches highlight the lack of harmonisation across regions. This results in non-uniform, fragmented datasets that hinder cross-Regional analysis and limit the development of coherent, large-scale soil and water management strategies, making large-scale hydrological modelling particularly challenging.

The aim of this study is to address the lack of homogeneous of soil data in the Po Plain by combining fragmented datasets to create the first standardised, high-resolution (1:50,000) map of soils and soil hydraulic parameters for the entire Plain. Hydraulic parameters were assessed using the most appropriate Pedotransfer Functions (Rawls and Brakensiek, 1989; Ungaro et al., 2005), which have previously demonstrated reliable performance across the diverse soil types of the Po Plain.

The paper is structured with two different branches, one aimed at the production of the soil map and the other describing the application of the Pedotransfer Functions to estimate the hydraulic properties, as shown in Fig. 1.

2. Materials and methods

2.1. Study area

The study area (hereafter referred to as Po Plain) coincides with the lowland areas of the Po River Basin District, managed by the Po River Basin Authority (AdBPo), as defined in accordance with the Water Framework Directive (2000/60/EC; European Parliament and Council, 2000) (see Fig. 2). The study area extends over 35,053 km^2 and includes the whole Po River Plain plus some additional territories south of the Po delta and is shared by four different Italian Regions: Piedmont, Lombardy, Veneto (partially) and Emilia-Romagna, as illustrated in Fig. 2. The Po river, stretching 652 km, is the longest watercourse in Italy; it originates close to the French border at Pian del Re on Mount Monviso (Turin) and flows eastward across Northern Italy, passing through cities such as Turin, Piacenza, and Cremona, before reaching the Northern Adriatic Sea near Venice, where it forms an extensive delta (Fig. 2). Positioned between the Alpine and Apennine mountain chains, the Po River Basin District cover a total area of 86,859 km^2, the majority of which

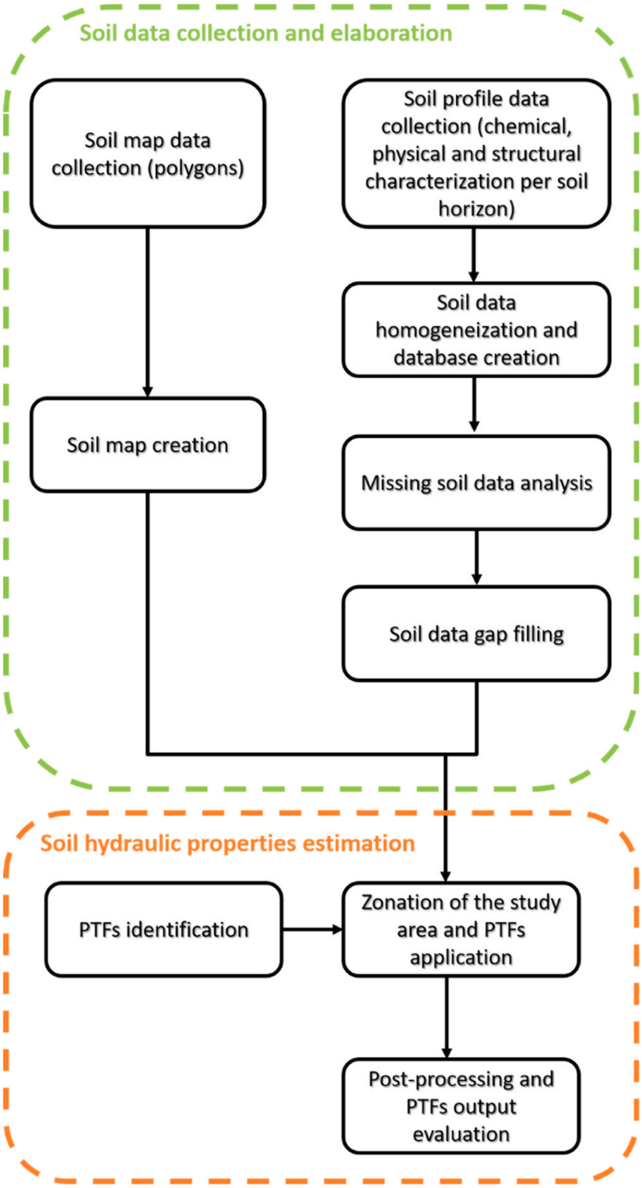

Fig. 1. Flowchart illustrating the general structure of the current study.

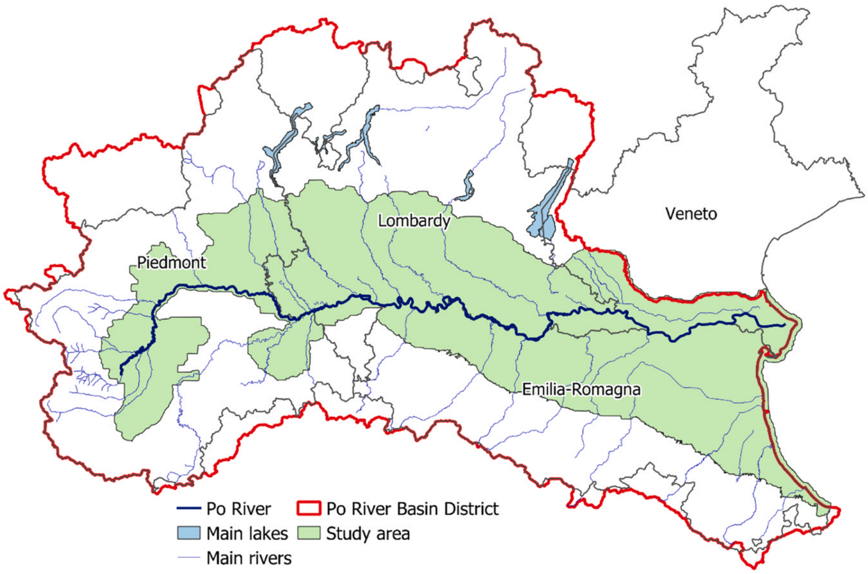

Fig. 2. Study area overview.

(82,788 km^2) lies within Italian territory (Autorità di Bacino Distrettuale del Fiume Po AdBPo, 2023). The Po River holds the highest average daily discharge in the Italian peninsula, with a mean flow rate of 1470 m^3 /s (Montanari, 2012). As reported by the Po River Basin Authority (Autorità di Bacino Distrettuale del Fiume Po AdBPo, 2006), around 60% of the basin's annual precipitation is converted into runoff at its outlet. The river flows through Italy's most economically productive areas, responsible for more than 50% of the national GDP, where its waters are heavily exploited for irrigation (average annual withdrawal of 12 billion cubic meters), for both civil and industrial uses (average annual withdrawal of about 3 billion cubic meters) and for hydropower production (Autorità di Bacino Distrettuale del Fiume Po AdBPo, 2023). This makes the Po River basin a highly complex and strategically vital system for the country, both environmentally and economically.

The Plain has a humid, sub-continental to continental climate (Fratianni and Acquaotta, 2017), with usually low wind conditions and high values of relative humidity increasing from south to east due to the peculiar conformation (Vallorani et al., 2018). The annual precipitation is between 600 and 1500 mm, mainly distributed in spring and autumn months. The lowest rainfall values are in the easternmost sectors, the highest are in the areas close to the Alpine fringe (Fratianni and Acquaotta, 2017). Thirty-years (1961–1990) mean annual temperature ranges between ca. 11°C and 14°C °C, with the lowest values in the westernmost parts of Piedmont at higher elevation, and the highest values approaching the coast (Fratianni and Acquaotta, 2017).

The Po River District accounts for approximately 50% of Italy's total irrigated land (ISTAT, 2020). Key cultivated crops include forage, maize, winter cereals, industrial crops, rice (predominantly in the area between Piedmont and Lombardy), vineyards, and a variety of horticultural crops (mainly in the central and eastern sectors) (Autorità di Bacino Distrettuale del Fiume Po AdBPo, 2006). The District's irrigation infrastructure is equally diverse and sophisticated. Water for irrigation is mainly supplied by river diversions, although groundwater extraction has increased in recent decades. Water is distributed through a vast network of irrigation canals, extending for approximately 70,000 km, many of which serve the dual purpose of drainage and irrigation (mixed-use canals) (Autorità di Bacino Distrettuale del Fiume Po AdBPo, 2023). Among them, about 6000 km are specifically dedicated to drainage function, especially in the low-lying eastern plains (Autorità di Bacino Distrettuale del Fiume Po AdBPo, 2006).

2.2. Soil data collection and map generation

Two complementary types of Regional soil information were collected: digital soil maps and soil profile data. Soil maps (GIS formats) are gathered from freely accessible Regional repository, i.e. Soil Map 1:50,000 for Piedmont, Lombardy, and Emilia-Romagna, and Soil Map 1:250,000 for Veneto (where the 1:50,000 soil map has not been published yet for considered part of the

Table 1
Summary of Po Plain Soil Map Data.

Region	Polygons	CUs	Soil Types	Horizons
Piedmont	3317	830	491	2148
Lombardy	3897	469	463	1928
Emilia-Romagna	1746	270	183	682
Veneto	146	20	20	66
Total	9106	1589	1157	4824

plain area). Each map is divided in Cartographic Unit (CU), each of them can be made up of one or more polygons. Each CU can also include either one or multiple soil types. For each CU, and consequently for each polygon, only the predominant soil type was considered and used in the following elaborations.

The summary of the soil map data, covering the number of polygons, CUs, soil types, and soil horizons per Region and for the entire Po Plain study area, is reported in Table 1.

To complement the soil map information, representative soil profile and structure data associated with the predominant soil types identified were collected from Regional pedological databases. The sources of the collected data are listed in Table 2.

The digital soil maps were gathered and some spatial gaps were observed in the Regional soil map coverage. Approximately 10% of the total study area was not covered by the available Regional soil maps data. For example, in Lombardy, urbanized areas and water bodies were not represented in the 1:50,000 soil map. To address this limitation, a spatial data extension algorithm was implemented. This algorithm extrapolated the soil information available from the existing soil maps across the entire study domain, using a calculation grid with 500 m × 500 m cells to systematically fill the gaps. The resulting spatial dataset was used for the Po Plain Soil Map generation.

2.3. Soil data homogenisation and database creation

Soil profiles, including structural aggregation data, extracted from the various Regional databases, were standardized and integrated into a single harmonized database, called the Po Plain Soil Database, preserving the original Regional coding systems despite their heterogeneity.

For Lombardy and Emilia-Romagna Regions, analytical values and descriptions of the representative soil profiles for each soil type are collected and stored separately by the respective Regional authorities (Table 2). Both data derived from analytical values databases and soil profile descriptions, such as structural aggregation, are however required in the Pedotransfer Functions application. These datasets often include more than one representative profile for the same soil type. Consequently, a substantial effort was required to associate the structure data with the corresponding horizons of the soil profiles imported into the Po Plain Soil Database.

Furthermore, a harmonization process was carried out for the soil structure data, converting the diverse Regional coding systems. The classification proposed by Ungaro and Calzolari (the coding scheme used in the PTF developed by Ungaro et al., 2005) was selected and the details about Regional coding system and their conversion in the Ungaro and Calzolari code are available in the Supplementary Materials (see Table S1-S10).

Analytical data were collected by each Regional authorities following standard methods (MiPAF, 2000).

The structure of the harmonized Po Plain Soil Database is illustrated in Table 3. Each field represents a column in the Database, while each row of the Database contains the data associated with a single soil horizon.

2.4. Missing soil data and gap-filling procedure

Once all the profile and soil structure data was compiled within the Po Plain Soil Database, a completeness analysis was carried out. Table 4 shows the percentage of soil horizons with missing data for four key attributes (Texture, Structure, Coarse Fragments and Organic Carbon (CO)), after the harmonization of Regional soil databases.

Texture showed the highest fraction of missing values in Piedmont (32%), while Emilia-Romagna had a relatively low fraction (5%). No missing texture data are reported for Lombardy and Veneto. Structure data exhibit notable gaps in Emilia-Romagna (28%) and to a lesser extent in Piedmont (16%) and Lombardy (13%), while data for Veneto are unavailable. Coarse fragments data are partially missing in Piedmont (10%), with no missing values reported for the other Regions. Organic Carbon (CO) data are substantially incomplete in Piedmont (47%), while Emilia-Romagna has minimal missing values (3%). All CO data are available for Lombardy and Veneto. Overall, Piedmont showed the highest percentages of missing data across most variables, especially for Organic Carbon and Texture, while Emilia-Romagna has moderate gaps, and Lombardy and Veneto presented more limited gaps in the available data.

This analysis underscores the variability in data completeness across Regional databases and emphasizes the necessity for targeted strategies to fill the identified gaps, particularly in Regions having large fractions of missing data such as Piedmont and Emilia-Romagna. To address these gaps, several phases of data completion were implemented, relying on the following three step gap-filling.

First gap-filling phase - Integration of additional data sources to complement the existing datasets: wherever possible, additional data have been sourced from regional monitoring networks, through request to the Regional authorities. The integration process

Table 2
Regional data sources for soil profile and structure.

Regional Organization	Data Source	Data Acquisition Method
Piedmont – IPLA (Institute for Wood Plants and Environment)	Database of soil profiles	Partially freely available online
Lombardy – ERSAF (Regional Agency for Services to Agriculture and Forestry)	i) Database of soil profiles ii) Soil structure data database	On request
Emilia-Romagna Regional Authority	i) Database of modal soil profiles ii) Soil structure database	On request
Veneto – ARPAV (Regional Agency for Environmental Prevention and Protection)	Interactive 1:250,000 soil map, with soil profile data	Freely available online

Table 3
Structure of the Po Plain Soil Profile Database.

Field	Definition
REGION	Region where the soil is located
SOIL ID	Unique numeric code identifying the soil type
SOIL NAME	Alphanumeric code identifying the soil type
N_HORIZON	Horizon number
GEN_HOR	Genetic horizon code (Soil Survey Staff, 1994)
LIM_SUP	Upper boundary of the horizon [cm]
LIM_INF	Lower boundary of the horizon [cm]
TEXTURE	Soil texture class (Soil Survey Staff, 1999)
%_CLAY	Clay content [%]
%_SILT	Silt content [%]
%_SAND	Sand content [%]
%_COARSE_SAND	Coarse sand content [%]
%_COARSE_SILT	Coarse silt content [%]
SKELETON	Coarse fragments content [%]
ORGANIC_CARBON	Organic carbon content [%]
BULK_DENS	Bulk density, calculated using the Ungaro Pedotransfer Function (Ungaro, 2007) based on %_SAND, %_CLAY, and ORGANIC_CARBON (for Emilia-Romagna Region only)
HYD_GROUP_USDA	Hydrologic Soil Group classification indicating the soil's potential runoff response, following the "Runoff Curve Number Method" (USDA, 1972) (for Lombardy Region only)
ORIGINAL REGIONAL STRUCTURE CODE	Structure degree, size and type according to the original regional codes, adapted from Soil Survey Staff (1994)
UNGARO AND CALZOLARI STRUCTURE CODE	Structure degree, size and type according to Ungaro and Calzolari codes (Ungaro et al., 2005)

Table 4
Percentage of horizons with missing data following the harmonization of Regional databases.

	Piedmont	Lombardy	Emilia-Romagna	Veneto
Texture	32%	-	5%	-
Structure	16%	13%	28%	100%-
Coarse Fragments	10%	-	-	-
Organic Carbon (CO)	47%	-	3%	-

involved cross-referencing, and harmonization to ensure consistency with the existing Po Plain Soil Database structure and coding systems. Regarding texture and stone fragments for Piedmont, missing data were integrated using further information provided, upon request, by IPLA (Institute for Wood Plants and Environment) Piemonte. These additional datasets contained texture and stone fragments content values associated with the predominant soil types within each Cartographic Unit (CU). Data were initially structured according to two standardized depth intervals: 0–30 cm (topsoil) and 30–100 cm (subsoil); therefore, a harmonization process was required to ensure consistency with the horizon discretization of the profiles in the existing Po Plain Soil Database.

Second gap-filling phase - Application of expert judgment and estimates to provide informed approximations: in cases where measured data or reliable supplementary sources were unavailable, domain expert applied their knowledge of Regional soil characteristics and pedogenetic processes, to infer missing values. For instance, gaps in soil structure data were addressed through expert-based estimations, guided by the characteristic structural properties typically associated with each genetic soil horizon, as summarized in Supplementary Materials (see Table S11). Finally, missing organic carbon data were filled by assigning typical values for each genetic horizon type in the Po Plain, differentiated by land use context (agricultural, forest, or grassland environments), as reported in Supplementary Materials (see Table S12).

The percentages of horizons with missing data after the first and second gap-filling phase are reported in Table 5.

Third gap-filling phase - Utilization of automated statistical algorithms for data completion: the remaining missing values were systematically addressed using an automated gap-filling algorithm, associated to the missing data relative to: i) texture, ii) structure, and iii) coarse fragments.

Where percentages of sand, silt, and clay were missing:

Table 5
Percentage of horizons with missing data after first and second phase of data completion.

	Piemont	Lombardy	Emilia Romagna	Veneto
Texture	12%	-	3%	-
Structure	1%	-	1%	-
Coarse fragments	1%	-	-	-
Organic Carbon	-	-	-	-

- if textural class was available (occurring only in the Piedmont Region), the missing values were estimated using the mean values of the horizons belonging to the same textural class within the same Region;
- if only the genetic horizon type was available, mean values associated with that specific horizon type were applied.
- if a complete absence of texture data occurred and if the horizon with the missing values was positioned at the beginning or end of a soil profile, values from the nearest adjacent horizon within the same profile were used. Conversely, if the horizon with the missing values was located between two others, values were estimated through linear interpolation of the data from the immediately overlying and underlying horizons.

Where structure data were missing, values were estimated by interpolation from neighbouring horizons data within the same soil profile. In particular, for very top and bottom horizons, the value of the closest horizon was used.

Finally, where coarse fragment fraction data were missing (occurring only in the Piedmont Region), the few missing values were set to zero, which is the median value for this parameter in the Region.

Following the completion of this third gap-filling phase, the database was fully populated, harmonized, and ready for use in the subsequent Pedotransfer Functions application for the estimation of the hydraulic parameters.

2.5. Pedotransfer Functions selection

The choice of the Pedotransfer Functions (PTFs) applied in this study was based on previous studies conducted by the different Regional authorities that verified independently their performances.

The procedures adopted for estimating bulk density, water retention characteristics, and saturated hydraulic conductivity (Ksat) reflected the approach employed by Lombardy and Emilia-Romagna Regional authorities, whose methodologies had previously been tested and validated within these regions and demonstrated reliable performance across most of the study area, within different previous projects.

The methodology for the soil hydraulic parameterization in the Lombardy Region followed the guidelines and the parametric PTFs reported in Rawls and Brakensiek (1989). While not formally validated, this set of PTFs provided reasonable parameter estimates, yielding model outputs of practical utility. Indeed, since 2018, these PTFs were used to estimate soil parameters for the parametrization of the IdrAgra model on Lombardy in order to estimate crop water requirements in accordance with the Lombardy region's annual water budget survey (ANBI Lombardia, 2016-2024), according to the standardized methodology adopted with D.d.s. n.4346/2018 (Regione Lombardia, 2018). Moreover, the irrigation requirements produced by the IdrAgra model, using soil hydraulic properties derived through this methodology was successfully validated at the district scale (specifically, the Muzza irrigation district), by comparing the model's estimates with the actual volumes of water supplied to the district, adjusted for irrigation network losses (Vassena et al., 2012). Furthermore, the reliability and applicability of this approach were confirmed through further applications and site-specific studies conducted within the regional context (Masseroni et al., 2021; Wassar et al., 2016; Baroni et al., 2010).

According to this PTF methodology, Bulk density (BD) was estimated using a PTF requiring soil texture parameters (percentages of sand and clay) and organic carbon (OC) content as input variables. This PTF was developed by Jeffrey (1970) and was adopted by Rawls and Brakensiek (1989). Then, porosity was estimated based on bulk density and the average real density of the mineral fraction (2.65 g/cm^3) (Rawls and Brakensiek, 1989). Finally, the PTFs were employed to estimate the Brooks and Corey model parameters (Brooks and Corey, 1966). These parameters were then converted in Van Genuchten model parameters (Van Genuchten, 1980), from

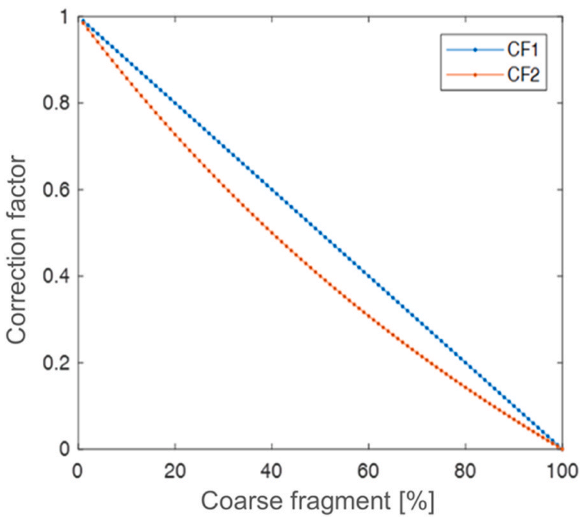

Fig. 3. Correction methodology applied for the presence of stone fragments content to the specific water content and to Ksat, developed by Rawls and Brakensiek (1989), used in the Lombardy methodology.

which soil water retention characteristics and saturated hydraulic conductivity (Ksat) were derived (Rawls and Brakensiek, 1989). In this case, input variables required were sand and clay percentages, organic carbon content, the previously estimated bulk density and porosity. After the PTF application, a correction had been applied to account for the presence of coarse fragments (Fig. 3). In agreement with the formulations proposed by Rawls and Brakensiek (1989), the presence of stones (in terms of volumetric stone content) reduced both soil water retention values (Eq.1) and Ksat (Eq.2).

$$\theta_{corr} = \theta \bullet CF1 = \theta \bullet (1 - \frac{SK_V}{100}) \quad (1)$$

$$Ksat_{corr} = Ksat \bullet CF2 = Ksat \bullet \quad 2 \bullet \quad \frac{1 - \frac{SK_V}{100}}{2 + \quad \frac{SK_V}{100}} \quad (2)$$

with:

θ_{corr}: generic soil water retention value corrected for the presence of stone fragments [m^3/m^3];

θ: generic soil water retention value [m^3/m^3];

SK_V: volumetric stone fragments content [m^3/m^3].

The Emilia-Romagna Region developed an approach combining the use of various Pedotransfer Functions (PTFs), some sourced from literature and others developed from scratch and calibrated on a wide database of Regional soils, to estimate the BD and the hydraulic parameters of soils based on their specific pedological characteristics. The effectiveness and performance of the selected PTFs for Emilia-Romagna soils were documented in previous Regional studies (Regione Emilia-Romagna (Tarocco, Calzolari, Ungaro) (2021a); Regione Emilia-Romagna (Tarocco, Aprea) (2021b)).

In this approach, Bulk Density (BD) served as input variable for the PTF-based estimation of soil hydraulic parameters and was derived using specific PTFs tailored to the genetic soil horizon and geographic zone, as detailed in Table 6.

The estimation of characteristic values of the soil water content (at saturation, field capacity and wilting point) was performed using a parametric Pedotransfer Function (PTF) developed by Ungaro et al. (2005), which estimates the parameter of the Van Genuchten model (Van Genuchten, 1980). These parameters were then used to derive the characteristic soil water content values (Ungaro et al., 2005). The PTF required, as input data, percentages of sand, clay and silt, organic carbon content, previously estimated bulk density and soil structure parameters. Saturated hydraulic conductivity (Ksat) was estimated using the Rawls and Brakensiek (1989) PTF, as recommended by Regione Emilia-Romagna (Tarocco, Calzolari, Ungaro) (2021a).

To identify the most appropriate PTFs approach, for each soil type, the study area was zoned based on granulometric properties and soil texture distribution. The area was subsequently divided into two homogeneous zones, each associated with a specific PTF approach.

3. Results and discussion

3.1. Po Plain Soil Map

As a result of the extensive collection, harmonization, and processing of Regional soil mapping data, the Po Plain Soil Map was generated (Fig. 4). Each polygon in the map is characterized by a unique identifier code. Additionally, each polygon is associated with a Cartographic Unit (CU) code. Conversely, a single CU might be associated with multiple polygons. Moreover, each CU includes an identifier code indicating the associated predominant soil type. The Po Plain Soil Map is also connected to the Po Plain Soil Database that details the subdivision of each soil type into horizons. For each horizon, the corresponding soil properties and hydraulic

Table 6
List of PTFs for BD calculation, selected for soils in Emilia-Romagna (Regione Emilia-Romagna (Tarocco, Calzolari, Ungaro) (2021a)).

PTF	Requirements	Soil horizons where the PTF is applied	Input data	Reference
Hollis (2012)	Horizons with CO > 2.15%	Peaty O horizons and Ap horizons with high organic matter content	CO	Hollis et al. (2012)
Hollis (2012) ricalibrata	Generic A horizons and forest soil horizons	A horizons of forest soils in plains and hills	Sand, clay, CO	Hollis et al. (2012)
CNR-IBIMET (2017)	Generic A horizons	A horizons of permanent grasslands in plains	Silt and CO	Calzolari et al. (2017)
CNR-IBIMET (2013)	Generic Ap horizons	Ap, Ap1 and Ap2 horizons	Silt, clay, CO, Dg and Sg	Ungaro et al. (2013)
CNR-IBIMET (2013)	Generic B horizons in plains	B, Ap2, and buried horizons in plains	Sand, silt, clay, CO, Dg and Sg2	Ungaro et al. (2013)
CNR-IBIMET (2013)	Generic B horizons in hills	B, Ap2, and buried horizons in hills	Silt, clay, CO, Dg and Sg2	Ungaro et al. (2013)
CNR-IBIMET (2013)	Generic C horizons in plains	C horizons in plains	Sand, silt, clay, CO, Dg and Sg2	Ungaro et al. (2013)
CNR-IBIMET (2013)	Generic C horizons in hills	C horizons in hills. Not applied to paralithic Cr horizons	Sand, silt, clay, CO, Dg and Sg2	Ungaro et al. (2013)

Dg = Structure grade; Sg = Structure shape/form; Sg2 = Secondary structure form

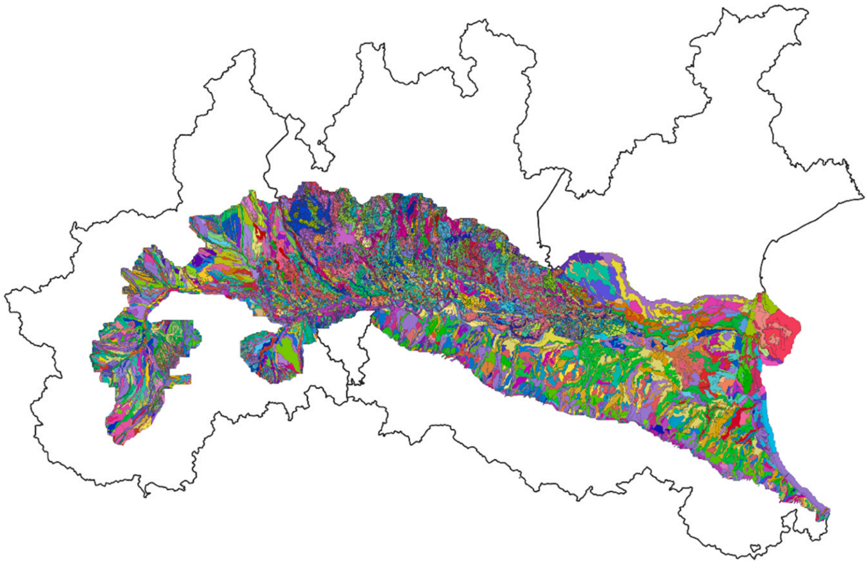

Fig. 4. Po Plain Soil Map, created joining the 1:50,000 soil maps from Piedmont, Lombardy, Emilia-Romagna regions and 1:250,000 soil map from Veneto Region, completed in the missing domain areas with the spatial data extension algorithm.

parameters, estimated in the previous sections, are included.

The Po Plain Soil Map describes a heterogeneous and detailed pedological context. 9106 polygons were collected, with 1589 CU and 1157 soil types described, subdivided in 4824 horizons (Table 1). The number of horizons, for each soil type, is variable on the basis of the specific characteristics, with a discretization between 1 and 8 horizons. Particularly, 36% of soil types have 4 horizons, while 25% and 22% of them have respectively 3 and 5 horizons. The distribution of the number of the soil horizons per soil type of the Po Plain Soil Database is reported in the supplementary materials (Figure S1).

3.2. Zonation of the study area and Pedotransfer Function (PTF) application

To identify homogeneous zones within the study area for the selection of Pedotransfer Functions (PTFs) approach to be used (see 2.5), several spatial factors were taken into consideration. These include granulometric properties and soil texture distribution, mostly associated with geographical location, distinguishing areas usually located on the left bank of the Po River from those on the right bank. In particular, concerning granulometric properties, soil texture triangles containing the horizons of soils from Piedmont, Lombardy, Emilia-Romagna and Veneto Regions was analysed and reported in Fig. 5.

Fig. 5 displays the soil texture triangles, which encompass all the horizons from soil profiles within the study area, categorized by Region. It is evident that soils in Piedmont and Lombardy are similar, with coarser textures, while those in Emilia-Romagna are finer. These differences arise from the river basins that deposited the original alluvial materials upon which the soils developed. Alpine rivers carry harder, crystalline rock material, while Apennine rivers collect less consolidated, finer-grained materials. In contrast, soils in Veneto show a hybrid behaviour, with coarser materials from Alpine origin in the upper regions, and clays and finer materials deposited in low-energy alluvial environments in the lower parts of the plain. Tectonic movements associated with the Alpine and Apennine orogenesis are also involved in the differentiation of soil granulometry between high-energy alluvium in Piedmont, Lombardy and the northern part of Veneto and the low-energy depositional environment in rest of the area. In fact, rivers in the northern side of the plain tend to flow inside valleys which are actively being eroded because of slightly uplifting tectonic movements. In contrast, a part of Veneto and most Emilia Romagna are characterized by mild subsidence, and thus rivers flow at or above the main plain level (Maesano and D'Ambrogi, 2016).

It is also important to note that fewer horizons were analysed for the Veneto Region, due to the limited extent of its territory within the study area and due to the coarser resolution of the data.

The distribution of soil texture within the study area was also considered, particularly the cumulated silt and clay content at 0–1 m depth (Fig. 6).

Fig. 6 reveals differences in soil silt and clay content between areas located on the left and right banks of the Po River, transcending Regional administrative boundaries. The soil texture analysis highlights how the Alessandria area (Piedmont), the Oltrepò Pavese and Oltrepò Mantovano (Lombardy) exhibit similar fine materials content to the soils of Emilia-Romagna. All these regions share materials of Apennine origin, which contribute to have a high content of clay and silt materials. A similar behaviour is shown by soils in the Rovigo province (Veneto), which is characterized by fine alluvial materials deposited in very low-energy, low-elevation environments.

Based on the analysis of granulometric properties and soil texture distribution, the study area was divided into two macro-areas of homogeneous soils; left bank of the Po River that includes Regions of Piedmont, Lombardy, and the portion of the Verona province

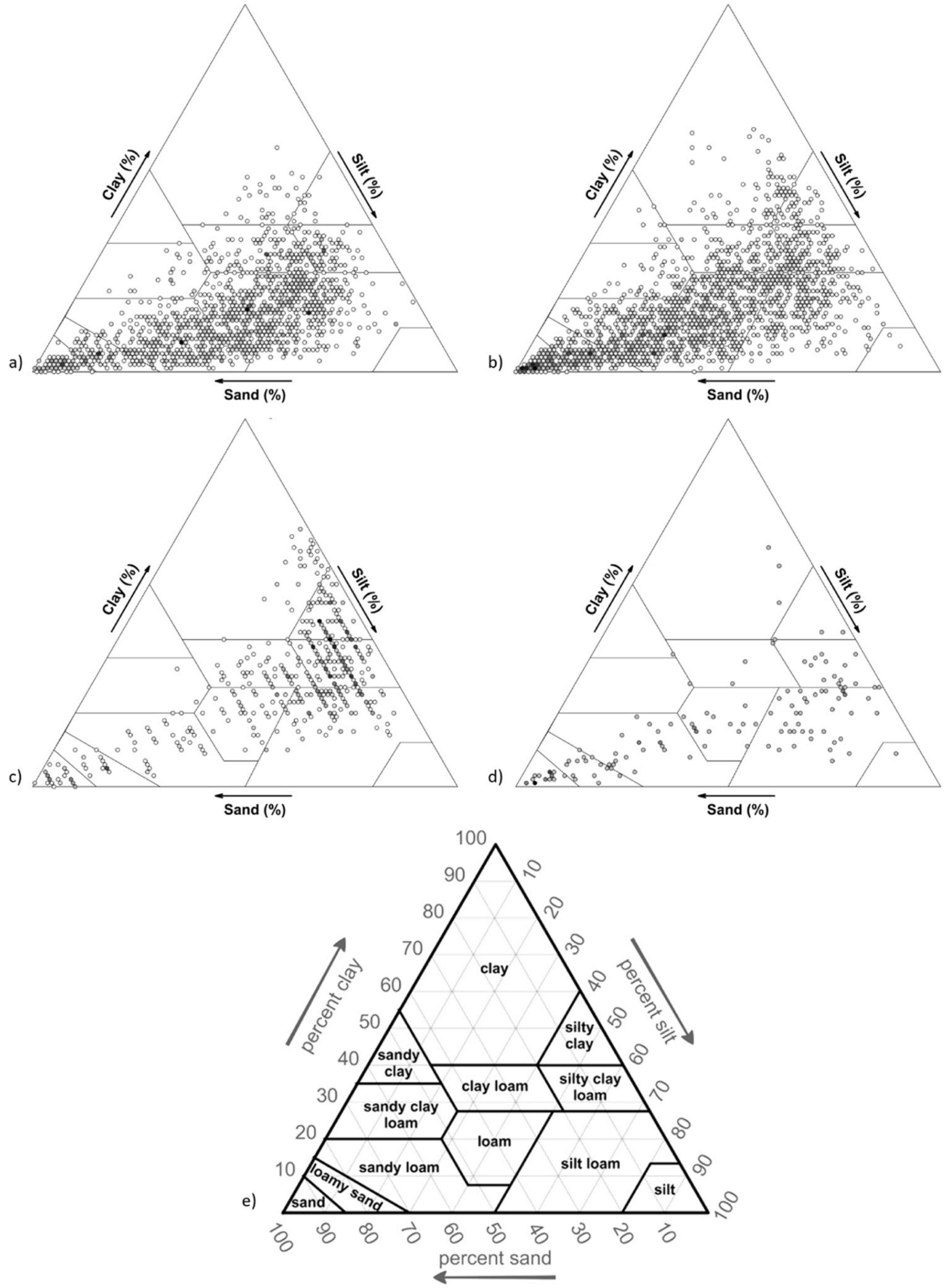

Fig. 5. Soil texture triangles containing the horizons of soils from a) Piedmont; b) Lombardy; c) Emilia-Romagna; d) Veneto; e) reference texture triangle.

falling within the study area (depicted in purple in Fig. 7). Right bank of the Po River encompasses Emilia-Romagna Region (with some areas across the Po River located in Lombardy), Alessandria province, Oltrepò Pavese, Oltrepò Mantovano, and the portion of Rovigo province of within the study area (depicted in green in Fig. 7).

For each macro-area identified in Fig. 7, a specific set of Pedotransfer Functions (PTFs) was applied, according to the approaches described in 2.5:

- left bank of the Po River: the Rawls and Brakensiek (1989) PTF was used for both the estimation of the retention curve and saturated hydraulic conductivity (Ksat), utilizing the Bulk Density (BD) estimated with the Rawls and Brakensiek (1989). This approach aligns with the methodology adopted for the soils of the Lombardy Region;

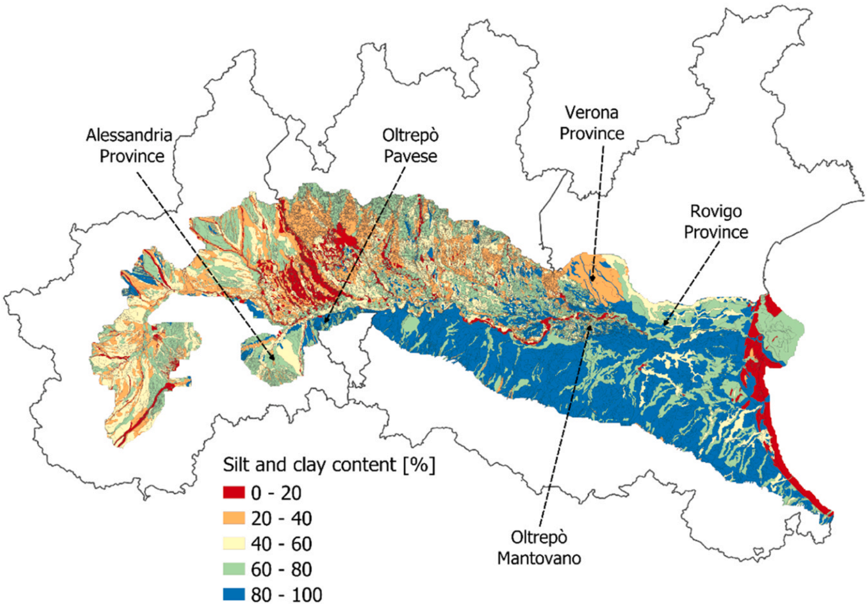

Fig. 6. Average of the sum of silt and clay content [%] at 0–1 m depth, for each polygon of the Po Plain Soil Map.

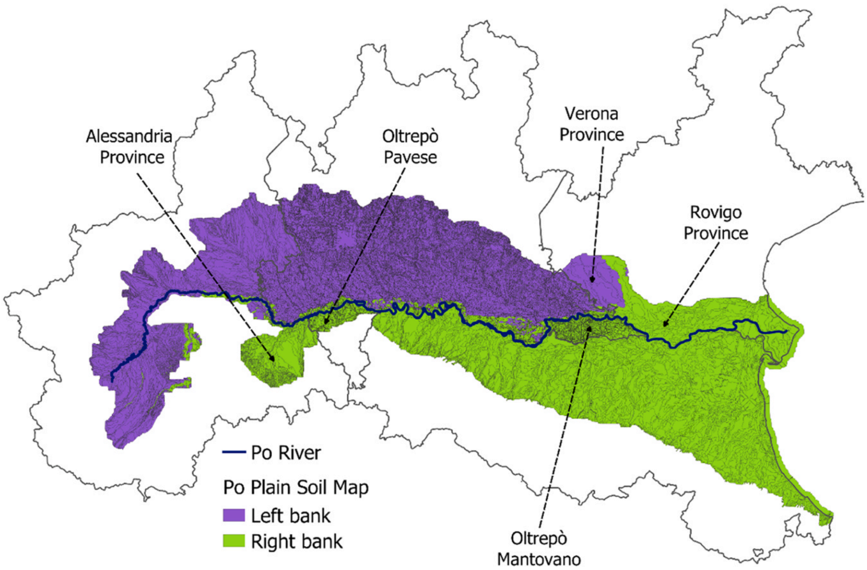

Fig. 7. Subdivision of the study area into Right and Left bank of the Po River.

- right bank of the Po River and south-east part of Veneto sector: the Ungaro et al. (2005) PTF was used for the estimation of the retention curve, employing the methodology applied for the BD estimation in the Emilia-Romagna Region (BD RER) (Table 6). For the estimation of Ksat, the Rawls and Brakensiek (1989) PTF was applied using BD RER, in line with the approach used by the Emilia-Romagna Region for its own soils.

3.3. Post-processing of PTF outputs

After the application of the Pedotransfer Functions (PTFs), the estimated values of BD and Ksat were adjusted, for a few genetic horizons, based on expert estimation. These adjustments were made according to typical characteristics derived from specific pedogenic and geomorphological processes and the FAO classification of permeability classes (FAO, 2006), as shown in Table 7.

R horizons (hard bedrock in place) consistently have BD values exceeding 2 g/cm^3 and extremely low Ksat values. R/C horizons (partially fractured rock) have slightly higher Ksat compared to R horizons. Horizons with the "ss" suffix indicate "vertic" properties, meaning a high presence of expandable clays, leading to swelling of the whole soil mass when moist, creating strong pressures leading to very fine porosity, high density and low Ksat. Horizons with the "x" suffix indicate fragic horizons, characterized by extreme compaction, likely due to past permafrost or deep seasonal frost during the Pleistocene glaciations (Van Vliet, Langohr, 1981; D'Amico et al., 2019). The deep freezing of these soils, which are often rich in silt, led to an extremely compact prismatic or laminar structure, associated with BD values exceeding 1.65 g/cm^3 and very low porosity (Bockheim and Hartemink, 2013). These horizons are known in literature as nearly impermeable and often remain dry even after particularly rainy seasons. Horizons with the "v" suffix represent soils formed in ancient periods, characterized by the formation of iron crusts (plinthite, petroplinthite, petroferric horizons) due to significant density changes (e.g. Costantini and Priori, 2007; D'Amico et al., 2025). The underlying layers are characterized by low permeability, and the iron crust serves as another barrier that water struggles to penetrate. Similarly, Btc horizons indicate the accumulation of iron (Fe) and manganese (Mn) concretions and nodules, typically associated with the presence of weakly permeable horizons below (e.g. Negri et al., 2021). Horizons with the "m" suffix, such as Bkm horizons, indicate cementation by pedogenic materials, which substantially limits permeability to levels slightly higher than those of bedrock, even though BD remains usually lower than 1.7 g/cm^3.

The calculated values were adjusted when they substantially deviated from the expected ranges (Table 7, column “Correction condition”). Overall, only 4% of the study area (397 polygons) consisted of soils containing horizons that required such corrections (Fig. 8). Table 7 shows that the estimated Ksat and BD values were considerably higher or lower than typical values for the examined horizons. This discrepancy is likely attributable to the strong influence of granulometry and of the structural aggregation data. In fact, the PTF by Rawls and Brakensiek (1989), applied on the left bank of the Po River, does not account for soil structure. For this reason, most polygons containing the corrected genetic horizons are located on the left bank of the Po River (Fig. 8). In contrast, the Ungaro et al. (2005) PTF includes soil structure as an input parameter, resulting in only a limited number of corrected polygons.

3.4. *Evaluation of PTF outputs*

The results, derived from the application of the Pedotransfer Functions (PTFs) and refined through expert-based post-processing procedures, are evaluated and compared against available reference data from the literature to assess their consistency and reliability. A preliminary comparison focused on three key hydraulic properties: i) the available water capacity (AWC) and saturated hydraulic conductivity (Ksat) and ii) the estimated bulk density (BD).

3.4.1. *Available water capacity (AWC) and saturated hydraulic conductivity (Ksat)*

To evaluate the PTFs output, the AWC map was generated (Fig. 9a). In particular, Fig. 9a illustrates the spatial distribution of AWC across the study area, computed for a 100 cm soil profile depth, calculated as the difference between volumetric water content at field capacity and at the permanent wilting point, both estimated via the selected PTFs according to the adopted procedure.

This map was compared with a corresponding map produced by Munafò et al. (2021) for the entire Po-Venetian Plain, also calculated for a 100 cm soil depth (Fig. 9b). This map was produced using a methodology different from the one adopted in this study and using soil data gathered from Regional database at a lower resolution than the one used in our study (1:250,000 versus 1:50,000). Specifically, in the Munafò et al. (2021) methodology soil water contents at field capacity (FC) and at wilting point (WP), up to 100 cm depth, were estimated using the following approach: i) application of PTFs of Ungaro et al. (2005); ii) when data fell outside the calibration range of these regional PTFs, estimates were derived using the PTFs of Rawls et al. (2003); and iii) for horizons with high organic matter content, default values were applied, based on literature data and limited local measurements. Bulk density values needed for PTFs application were obtained as follow: i) when in the Regional soil database neither measured nor estimated value of bulk density was available, bulk density was estimated using one of the PTFs of ARPAV Regional Agency for Environmental Prevention and Protection Centro Veneto Suolo e Bonifiche (2019), selecting the most suitable according to organic carbon content; ii) then the estimated values falling below the 10th percentile or above the 90th percentile were corrected by replacing them with average values

Table 7
Correction rules for PTFs based on genetic horizon type and average estimated values before the correction.

Genetic horizon/suffixes	Variable	Average pre-corrected value	Correction condition	Corrected value
R	BD (g/cm^3)	1.46	< 2	2.3
R	Ksat (cm/d)	133.41	> 1	0.1
R/C	BD (g/cm^3)	1.34	Always	2.3
R/C	Ksat (cm/d)	16.61	Always	0.5
ss	Ksat (cm/d)	2.16	> 1	0.9
x	BD (g/cm$_3$)	1.37	< 1.6	1.65
x	Ksat (cm/d)	11.45	> 1	0.9
Bv	BD (g/cm$_3$)	1.39	< 1.6	1.65
Bv	Ksat (cm/d)	38.88	> 1	0.9
BCtc	BD (g/cm$_3$)	1.39	< 1.6	1.65
BCtc	Ksat (cm/d)	9.49	> 1	0.9
Ha,He	BD (g/cm^3)	0.46	Always	0.3
Ha,He	Ksat (cm/d)	59.39	Always	2.0
Ckm	Ksat (cm/d)	125.60	> 2	0.9
Btc	Ksat (cm/d)	32.90	> 10	10

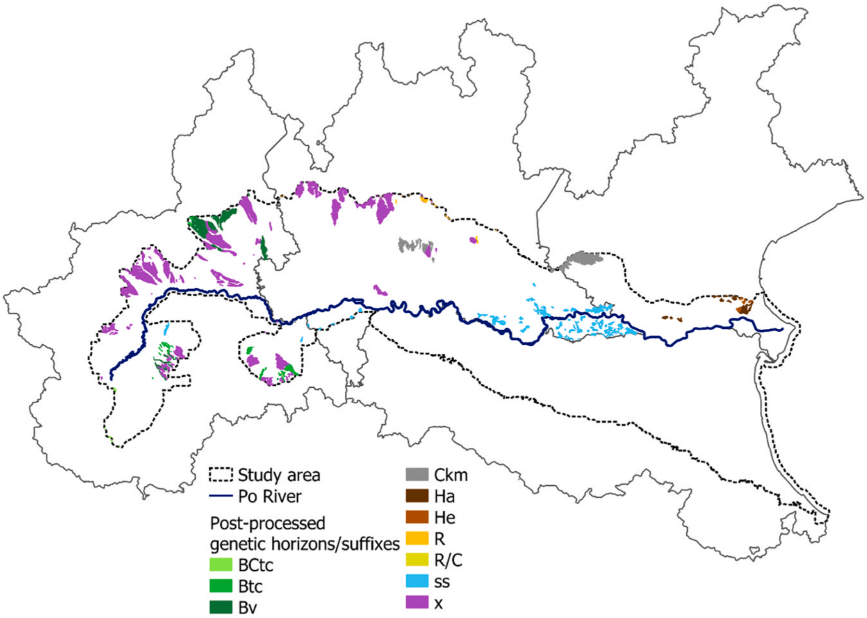

Fig. 8. Polygons with post-processed PTF output, according to genetic horizons / suffixes.

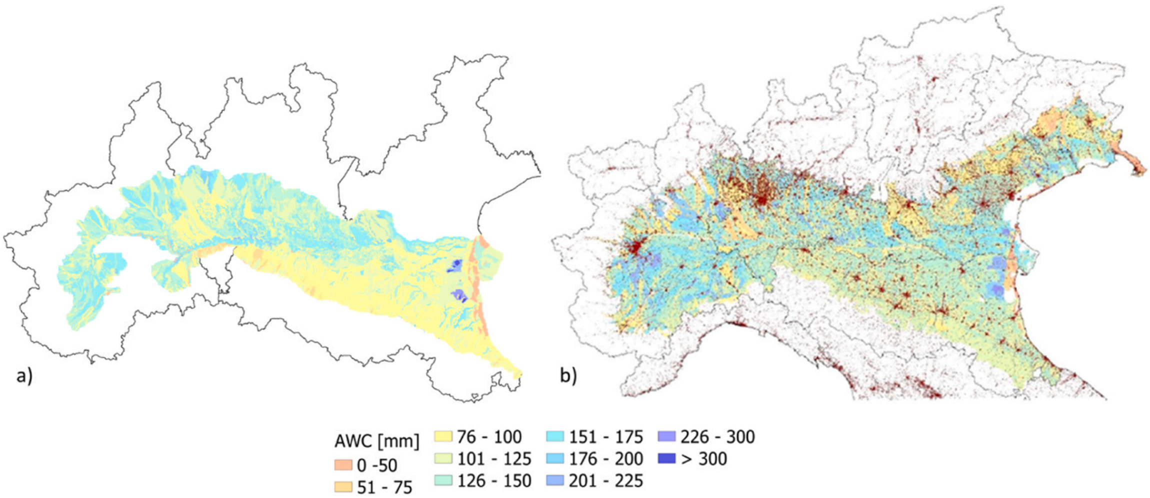

Fig. 9. Available Water Capacity (AWC in mm) in the soils of the Po plain, calculated over a 100 cm soil profile: a) estimated using the studied methodology; b) from Munafò et al. (2021), where the areas in red indicate zones affected by irreversible soil sealing.

corresponding to the respective soil texture class and organic matter content.

Finally, in the Munafò et al. (2021), AWC was calculated as the difference between soil water content at FC and WP, correcting the obtained values for the presence of coarse fragments, according to Eq. (3).

$$AWC_{corr} = AWC_{fine} * ((100 - SK)/100) + 0.3 * (SK/100) \tag{3}$$

with:

AWC_{corr}: AWC corrected for the presence of coarse fragments [m^3/m^3];

AWC_{fine}: AWC of the fine earth fraction [m^3/m^3];

SK: stone fragments content [m^3/m^3].

Despite the differences in methodologies and spatial resolution, the comparison between the two maps highlights a general agreement between the spatial patterns of AWC. While absolute values (in mm) may not always match perfectly, the relative distribution and gradients of available water capacity across the study domain are consistent, effectively capturing the differences and relationships among the various landscape units within the Po Plain. The alignment between the estimates from this study and data from other independent studies supports the reliability of the results.

A further analysis was conducted based on the Ksat hydraulic properties, reported in Fig. 10, which shows the map of Ksat of the upper soil layer (1 m depth), calculated as the geometric average value of the Ksat estimated, for each soil horizon included in the 0–1 m depth, using the PTFs following the previously described methodology.

From Fig. 9a and Fig. 10, clear differences emerge in soil types and their associated hydraulic properties within the study area. Comparing the left and right banks of the Po River, the left bank predominantly features coarser soils with higher Ksat and greater available water content (AWC), while the right bank generally exhibits lower values for both parameters. Interestingly, the occurrence of lower AWC in finer-textured soils compared to coarser ones is somewhat atypical. However, the potential range of AWC values within each texture class overlaps considerably. For instance, sandy loam soils with relatively high AWC can retain more water than certain clay soils with low AWC due to the micro-porosity that decreases the available water, as illustrated in Allen et al. (1998). This pattern is observed in the Po Plain, where coarse, high-AWC soils are found on the river's left bank, contrasting with fine-textured, low-AWC soils on the right bank. Structural aggregation type, which is an input parameter in the PTFs by Ungaro et al. (2005), is likely involved in such result. For example, vertic soils (ss suffix), with clayey Bss horizons characterized by compactness and high density (particularly when moist), present a reduced AWC mainly due to the very fine microporosity. These soils are very common in the right bank of the Po Plain.

3.4.2. Bulk density (BD)

The BD estimates obtained for the Emilia-Romagna Region were compared with reference values measured and provided by the Emilia-Romagna Regional authorities. These reference measurements were derived using the core sampling method, as specified in the analytical methods document accompanying the 1:50,000 soil map of the region.

The comparison covered 53 soil types and 207 individual horizons, across the entire available depth of the soil profiles. As in the case of the structural aggregation parameters (see 2.3), the integration required a harmonization step to align the measured BD data with the horizon discretization used in the Po Plain Soil Database. Specifically, an exact match in soil type, genetic horizon, and soil texture was identified for 78 horizons, while a partial match, limited to soil type and texture, was found for 129 horizons.

The results of the comparison (Fig. 11) show that the BD values estimated through the proposed methodology are aligned with the reference measurements from the Emilia-Romagna dataset, demonstrating a significant level of agreement ($R^2 = 0.64$), based on 113 horizons (55%) where the estimated and measured BD values differed by no more than ±10%. The paired *t*-test indicates no significant difference between the two bulk density estimates (ME = 0.006 g/cm^3; p value = 0.44), suggesting absence of systematic bias. The RMSE is 0.08 g/cm^3 (5.6%), indicating a relatively low dispersion between methods and overall good agreement. This degree of correspondence can be considered relevant given the high natural variability of soil properties.

3.5. General discussion

The soil map developed represents a significant advancement in terms of resolution and completeness for the entire Po Plain. Unlike data extracted from global datasets, such as the HWSD, which adopted a simplified two-layer structure (0–30 cm and 30–100 cm) (Poggio et al., 2021), this map includes a detailed vertical stratification with approximately 4–5 soil horizons per profile. A major contribution of this work is the systematic integration of previously missing data, particularly soil texture and organic carbon content. While some European-scale maps incorporating hydrological properties were developed (e.g., Szabó et al, 2024), they relied on the LUCAS database, but only the topsoil is available (0–20 cm), which strongly limits the possible use for agricultural purpose. Moreover, only 66 measured points are included overall the Po Plain (Panagos et al., 2024). In contrast, the map presented here offers a more comprehensive and usable resource for both agricultural and environmental analyses at the regional scale.

This enriched physical, chemical, and structural dataset enables the application of a wider range of Pedotransfer Functions (PTFs), including those requiring detailed input variables, such as the ones developed by Ungaro and Calzolari (Ungaro et al., 2005). In turn, this can improve the reliability of estimated soil hydraulic parameters and, consequently, the performance of hydrological and agro-hydrological models. In fact, prior to this work, available soil data for the Po Plain were fragmented and predominantly limited to Regional sources, often characterized by heterogeneous resolution, and incomplete spatial coverage. Although several recent studies conducted in the Po Plain, attempted to overcome these limitations by employing global or continental-scale soil databases, significant shortcomings remained (Poggio et al., 2021). For example, Busschaert et al. (2024) and De Lannoy et al. (2024) estimated irrigation requirements across the Po Valley using land surface models and assumed homogeneous soil texture classes throughout the soil profile based on HWSD data. This assumption is largely related to the limited vertical representation provided by HWSD data, which includes only two soil layers (0–30 cm and 30–100 cm) (Poggio et al., 2021).

These limitations constrain its effectiveness for precise, large-scale hydrological and irrigation requirement modelling. In contrast, the soil map developed in this study addresses these limitations by providing a comprehensive, high-detail, and regionally consistent dataset specifically tailored for hydrological modelling in the Po Plain. Its integration into large-scale simulations allows for a more realistic representation of soil properties and processes, improving the accuracy of water balance estimations and irrigation requirement assessments in this agriculturally strategic region.

A broader perspective on recent developments in soil–hydrological modelling further highlights the importance of high-quality input data. For instance, Ali et al. (2025) developed machine learning–based Pedotransfer Functions using SoilGrids-derived predictors to estimate spatially distributed hydraulic parameters and improve streamflow simulations across Great Britain, with transferability tested in France. Their approach demonstrates the growing reliance on global soil products combined with data-driven techniques to compensate for limited field observations. However, in their framework, a key parameter (fKh0, the ratio between

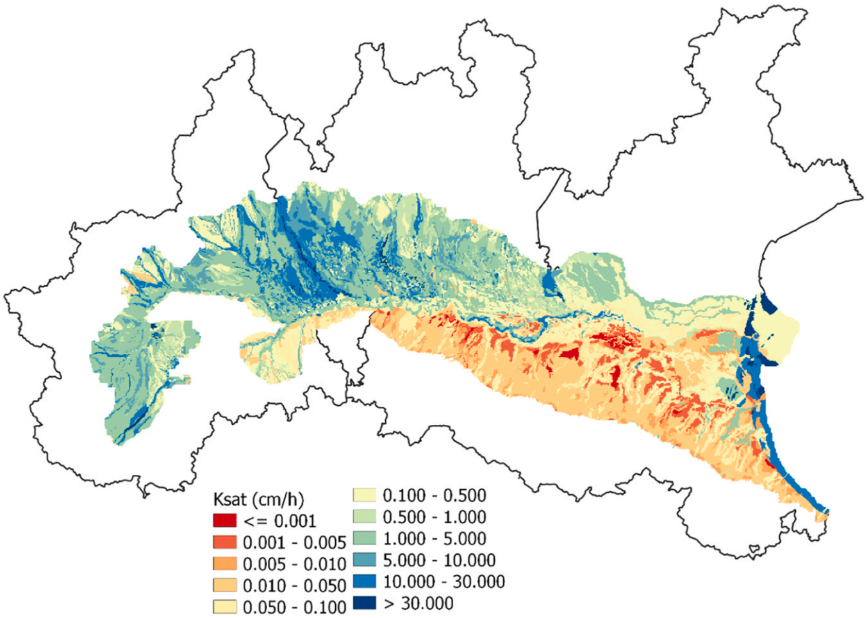

Fig. 10. Saturated Hydraulic Conductivity (Ksat in cm/h) in the soils of the Po Plain, calculated over a 100 cm soil profile.

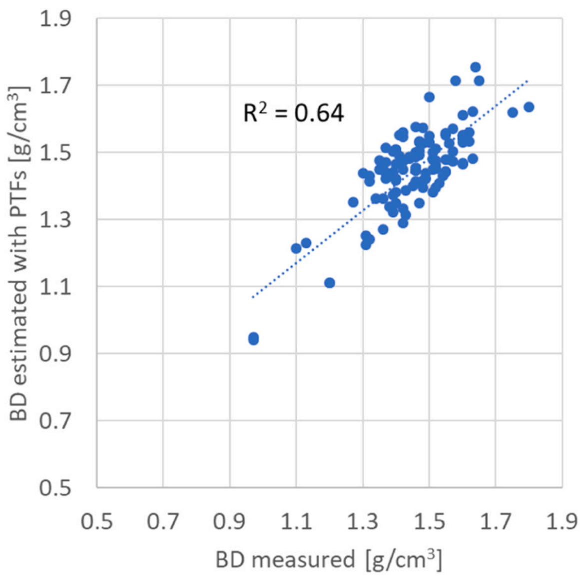

Fig. 11. Comparison between Bulk Density (BD in g/cm^3) measured and provided by the Emilia-Romagna Region (x-axes) and estimated using the studied methodology (y-axes), on the available depths of the different soil profiles.

horizontal and vertical saturated hydraulic conductivity) required calibration against observed discharge (CAMELS-GB), particularly when applied to regions with contrasting pedological and geological settings. As a result, it may have compensated not only for real soil properties but also for further model parameter uncertainties, reducing its physical meaning and limiting its transferability to other regions. In addition, the training dataset covered a limited range of soil types, which likely contributed to lower performance under different geological conditions.

In this context, the high-resolution, horizon-based soil map developed for the Po Plain offers a more comprehensive and vertically explicit soil information base. Rather than relying on globally harmonized but simplified soil inputs, it enables the direct application of physically based or semi-empirical PTFs using detailed, measured soil information. This strengthens the physical consistency of large-scale agro-hydrological simulations.

4. Conclusions

Although soil maps serve a wide range of environmental and land management purposes, the present study focuses on their use for enhancing water management and planning in the Po Plain area, characterized by complex hydrological dynamics and intensive agricultural activity. This work represents the first effort to produce a harmonized, spatially continuous map of soil types and hydraulic properties covering the entire Po Plain at a consistent resolution and level of detail. Until now, no homogeneous soil database of this kind had been available for the area, with existing information scattered across Regional datasets, each based on different methodologies, formats, and levels of completeness. By integrating these heterogeneous sources through a systematic, expert-informed post-processing workflow and applying Pedotransfer Functions (PTFs) tailored to the specific soil conditions of the basin, this study has generated a coherent, reliable dataset of key hydrological soil parameters.

The resulting map not only serves as a crucial input data for hydrological modelling applications but also offers significant added value for the wider scientific community and institutional stakeholders. In particular, the River Po District Basin Authority, as the primary decision-making body for water resource management in the region, now has at its disposal a scientifically validated, spatially detailed dataset that can help water allocation strategies, risk assessment, climate adaptation planning, and land-use management. This foundational dataset establishes a solid basis for future studies and operational applications, enhancing the capacity for evidence-based, integrated water resource management across one of Italy's most important and complex hydrographic districts.

At this stage, the study has applied the two most suitable PTFs currently available for estimating the soil hydraulic parameters on the left-bank areas of the Po River, alongside those calibrated for soils on the right bank. Importantly, however, the database has been designed to retain all relevant physical and chemical soil data necessary for future applications of additional or alternative PTFs, thereby ensuring flexibility for a variety of study objectives or modelling frameworks.

A key area for future improvement of the soil map concerns the rice cultivation areas, which are extensive within the Po Plain and characterized by peculiar soil features. For these regions, estimations of hydrological properties will rely on PTFs that have been specifically validated for these soils through research carried out within the area (Tkachenko et al., unpublished results). These refinements will further enhance the precision of the soil property estimates, especially regarding water retention and permeability characteristics crucial for rice paddies. The inclusion of more tailored PTF for paddy soils will not only improve the overall quality of the soil map but also provide a better understanding of the complex hydrological processes governing rice farming, thus aiding in more effective water management and agricultural planning.

CRediT authorship contribution statement

Sara Cazzaniga: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Olfa Gharsallah:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. **Claudio Gandolfi:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Enrico Antonio Chiaradia:** Software, Formal analysis. **Michele Eugenio D'Amico:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Michele Rienzner:** Writing – review & editing, Software, Formal analysis.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2026.103488.

Data availability

Data will be made available on request.

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