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Research paper

Hydrogeological water budget in the Venetian alluvial plain for the sustainable management of groundwater (northeastern Italy)

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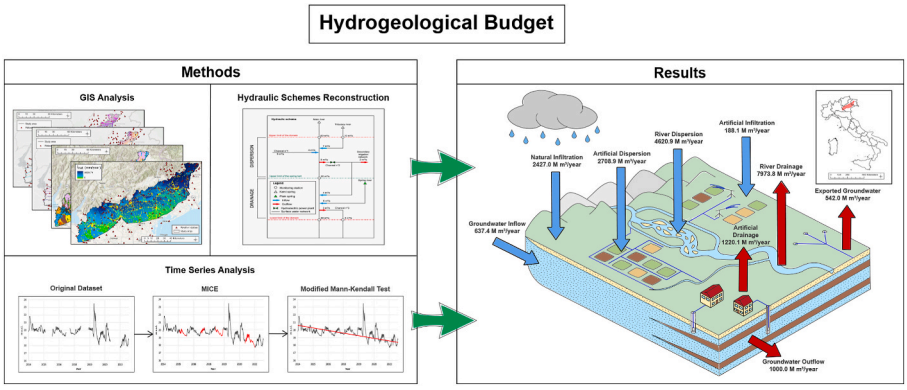
HIGHLIGHTS

- Hydrogeological mass balance in the Veneto–Friuli alluvial plain.
- Application of different methods to address heterogeneous and incomplete datasets.
- Implementation of missing data and modified Mann-Kendall trend analysis.
- Groundwater storage reduction caused by overexploitation.
- Water management strategies to prevent groundwater resource depletion.

GRAPHICAL ABSTRACT



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ABSTRACT

In this article, a regional-scale hydrogeological budget is presented for the upper and middle plain of the Veneto and Friuli-Venezia Giulia regions in northeastern Italy. This work provides a comprehensive conceptual model of groundwater processes in the study area, including quantitative estimates of inflows and outflows due to both natural processes (precipitation, river interactions, groundwater flows) and anthropogenic activities (irrigation, well pumping). These estimates represent the basis for discussions on the sustainability of water uses and offer a reliable dataset to constrain numerical simulation calibration.

Depending on data availability and quality, different methods were applied, including GIS-based analyses, water-use assessments, hydraulic scheme reconstructions, upscaling of available datasets, estimation of missing values in time series through a machine-learning approach, and statistical trend analyses (modified Man–Kendall test and Sen's slope estimation). This combination allowed the integration of heterogeneous datasets, often characterized by spatial and temporal gaps, to estimate the water budget terms.

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The results indicate the absence of a negative pluviometric trend over the budget period, while potentiometric levels show a negative trend in 16% of the monitored wells. The groundwater storage variation (ΔS), estimated through GIS-based analysis of level trends, decreases by approximately 153.6 M m^3/year.

By identifying the main processes and volumes involved in the regional groundwater cycle, the developed hydrogeological budget provides a quantitative framework for assessing changes in groundwater storage and represents a valuable basis for supporting sustainable water resource management in the study area.

1. Introduction

The growth of the global population, increasing urbanization and industrial development have led to a worldwide increase in water consumption, a crucial issue that is being addressed by securing new water supply sources and improving water resource management (Falkenmark, 2001; Flörke et al., 2013). These strategies are hindered by anthropogenic activities, which affect water resources through pollution and overexploitation, as well as by climate change, resulting in the variation and intensification of hydrological events (Olmstead, 2014; Green, 2016; Ficklin et al., 2022). These issues particularly affect countries with limited access to these resources, even leading to stability and national security concerns (Grey and Sadoff, 2007). Moreover, awareness of water security has begun to grow in countries that have long been rich in water (UN. ESCAP, 2001; Bakker, 2012). The need to ensure water availability for current and future generations has led to policies focused on protecting water resources, reducing human impacts, and aiming for sustainable development goals (SDGs).

In Europe, the main regulatory framework is the Water Framework Directive (WFD, Directive, 2000/60/EC; European Parliament and Council, 2000), complemented by the Groundwater Directive (GWD, Directive, 2006/118/EC; European Parliament and Council, 2006) and the Environmental Quality Standards Directive (EQSD, Directive, 2008/105/EC; European Parliament and Council, 2008), which set the key guidelines for proper water resource management. The need for a dedicated directive on groundwater stems from the high importance of this resource, as 65% of drinking water and 25% of water for agricultural irrigation in Europe are extracted from underground sources (European Environment Agency, 2022). Among European countries, Italy is among the main users of water, and the increasing frequency of extreme weather events, such as the 2022 drought and the 2023 Emilia-Romagna flood, further highlights the need for an integrated approach to water management. For effective planning, a deep understanding of the area of interest, including both environmental and human dynamics, is essential.

A method for characterizing the components of the water cycle is the hydrological balance, which supports the distinction and quantification of the water volumes associated with different balance components (Xu and Singh, 2004; Healy et al., 2007; Ivezic et al., 2017; Kampf et al., 2020; Silva-Júnior et al., 2021). This is particularly useful in water use planning, as it highlights the impacts of withdrawals and human activities on the total water volume circulating within the analyzed area; in addition, understanding the relationship between inflows and outflows is useful for assessing potential variations in the volume of the resource (Kouassy Kalédjé et al., 2020; Chatterjee et al., 2025). The hydrogeological balance is implicitly a component of the classical hydrological balance, but since groundwater represents a primary water supply source, analyzing this environmental compartment in detail and identifying and estimating the budget terms are essential (Bera et al., 2024; Kuang et al., 2024; Perera et al., 2024). Groundwater balances aimed at resource management are generally conducted at a regional scale, enabling public authorities to gain a comprehensive understanding of the territory under their jurisdiction; in this way, the scale of the assessment matches the scale of the management (Cash and Moser, 2000).

For these reasons, this paper presents the hydrogeological water balance determined in an area of approximately 8700 km^2 in northeastern Italy. The implemented water balance refers to the period 2010–2022, which covers a total of 13 years. This analysis aligns with Italy's general policy on water resource management because in recent years, various regions have developed their own water balances (Zini et al., 2011; Regione Lombardia, 2016; ARPA Piemonte, 2018), and a national-scale hydrological and hydrogeological model (BIGBANG) has been proposed by the ISPRA, the Institute for Environmental Protection and Research (Braca et al., 2023). In the present study, an analytical hydrogeological balance was conducted to support a public administration, the Eastern Alps Water Authority, and a comprehensive conceptual model for the study area was developed to quantify the variables that had the greatest influence on the recharge and depletion of the groundwater resource and assess the impact of anthropogenic activities on the system. The distinctive feature of the hydrogeological balance is the attempt to explicitly account for all significant balance terms in the study area. The quantification of the components of a regional-scale hydrogeological balance inevitably requires estimations, which must be based on available data and may involve the application of different methods (Meza-Gastelum et al., 2022; Yu et al., 2023; Brookfield et al., 2024; Abbas et al., 2025). In this paper, a GIS-based analysis of climatic data, the reconstruction of river hydraulic schemes, data collection on water use during human activities, and a Mann–Kendall trend analysis of precipitation and groundwater levels were performed to estimate different groundwater balance components. In addition to the obtained water volume values, which are believed to reasonably capture the magnitude of contributions to the hydrogeological balance, attention is given to the approaches used to estimate them. The choice of each of these methods was guided by the availability of data in the study area: more advanced methods were used where abundant information was available, and rougher upscaling techniques were applied where data were scarce (Gebru et al., 2024). These considerations help highlight the quality of the estimates and identify which aspects require further investigation to provide better decision-making support. For improved clarity in this assessment, estimate quality was systematically evaluated using a pedigree matrix (Weidema and Wesnæs, 1996).

The present hydrogeological balance was therefore designed to be simple, transparent, and scalable, allowing it to be progressively updated and refined as additional information becomes available. This approach reflects its intended role as an analytical calibration tool in support of a future distributed groundwater numerical model. In hydrogeological modeling, it is indeed common practice to calibrate models using the hydraulic head alone, often without a rigorous assessment of the associated flows; in contrast, the proposed hydrogeological balance enables the calibration of water mass-balance components and thereby provides a more robust and physically consistent approach.

2. Study area

The study area is located in the northeastern portion of the Po Valley, within the Veneto-Friulian plain, which includes the first northern mountain ranges (Fig. 1). The plain area is of alluvial origin and formed during the Holocene and Pleistocene through the deposition of fluvial and fluvioglacial sediments with alternating glacial and interglacial cycles. These processes led to the formation of megafans, which are large fan-shaped landforms that cover the entire plain area (Mozzi, 2005; Fontana et al., 2014). The structure of a megafan exhibits longitudinal

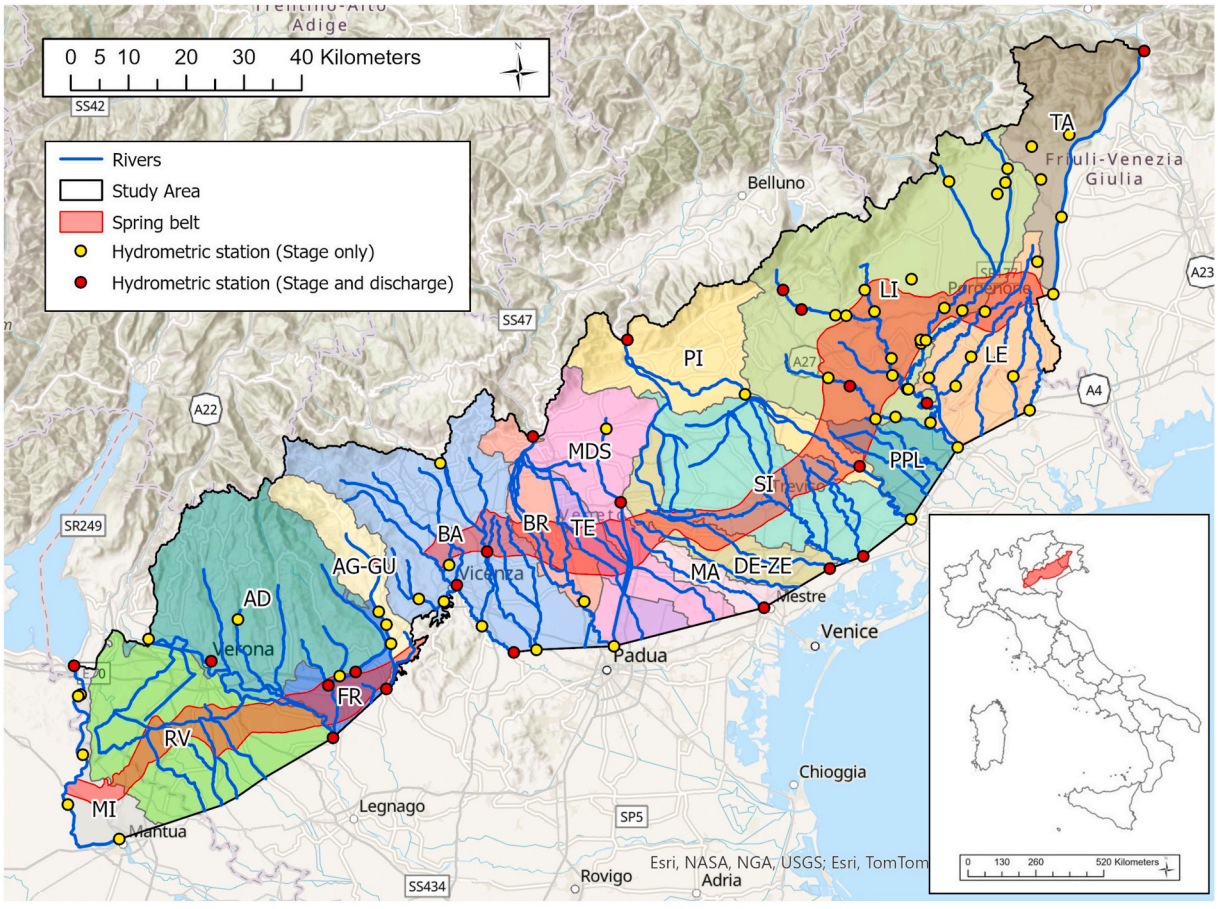
differentiation in terms of sedimentation, with coarse-grained materials in the proximal areas and fine-grained materials in the distal areas. For this reason, near the mountain slopes, the sediments are typically gravelly-sandy, whereas toward the sea, they predominantly consist of sand, silt, and clay. According to the variation in sedimentation, the plain can be divided into three zones, transverse to the principal flow direction of surface water and groundwater, namely, the high, middle, and low plain zones.

The high plain is composed mainly of gravelly-sandy sediments and hosts an undifferentiated phreatic aquifer of significant thickness, extending from the water table to the bedrock. In the southern part of the high plain, the water table intersects the land surface, resulting in the natural emergence of groundwater and the formation of a "spring belt" (Figs. 1 and 2a), a feature characteristic of the middle plain (Vorlicek et al., 2004; Pilla et al., 2006; Cucchi et al., 2008; Fabbri and Piccinini, 2013). The middle plain represents the transitional zone between the high and low plains and is characterized by a confined gravelly multiaquifer system. Further south lies the low plain, which is composed predominantly of fine-grained materials and alternating silty-clayey and sandy-silty layers deposited during the Quaternary glacial and interglacial cycles. Gravelly confined aquifers of the middle plain transition into sandy confined aquifers in the low plain.

The unconfined aquifer of the high plain and the confined multi-aquifer system of the middle–low plain are hydraulically connected: the high plain serves as the primary recharge area for the entire aquifer system, receiving inputs from rainfall infiltration, water losses from rivers and canals, irrigation return flows, and contributions from fractured mountain aquifers (Fabbri et al., 2016).

The implementation of a hydrogeological water balance required the definition of an appropriate domain, designed on the basis of the available information and aimed at the minimization of unquantifiable inflows or outflows. Therefore, the study area was defined with the following considerations:

- The northern boundary coincides with the watershed divides draining into the study area to prevent inflows from external basins and intersects the monitoring stations on alpine rivers to determine the discharge rates attributable to them;
- The lateral boundaries coincide with rivers that at least superficially act as hydrogeological divides, namely, the Mincio River to the west and the Tagliamento River to the east;
- The southern boundary follows the alignment of the river monitoring stations in the middle–low Venetian plain, allowing for the assessment of the outflows attributable to these rivers.



Watersheds

MI = Mincio basin
RV = Risorgive veronesi basin
AD = Adige basin
FR = Fratta basin
AG-GU = Agno-Gua' basin
BA = Bacchiglione basin
BR = Brenta basin
TE = Tergola basin
MDS = Muson dei Sassi basin
MA = Marzenego basin
DE-ZE = Dese-Zero basin
SI = Sile basin
PI = Piave basin
PPL = plain between Piave and Livenza
LI = Livenza basin
LE = Lemene basin
TA = Tagliamento basin

Fig. 1. Study area, watershed subdivision of the domain and hydrometric stations (yellow dots: water level monitoring stations; red dots: water level and discharge monitoring stations).

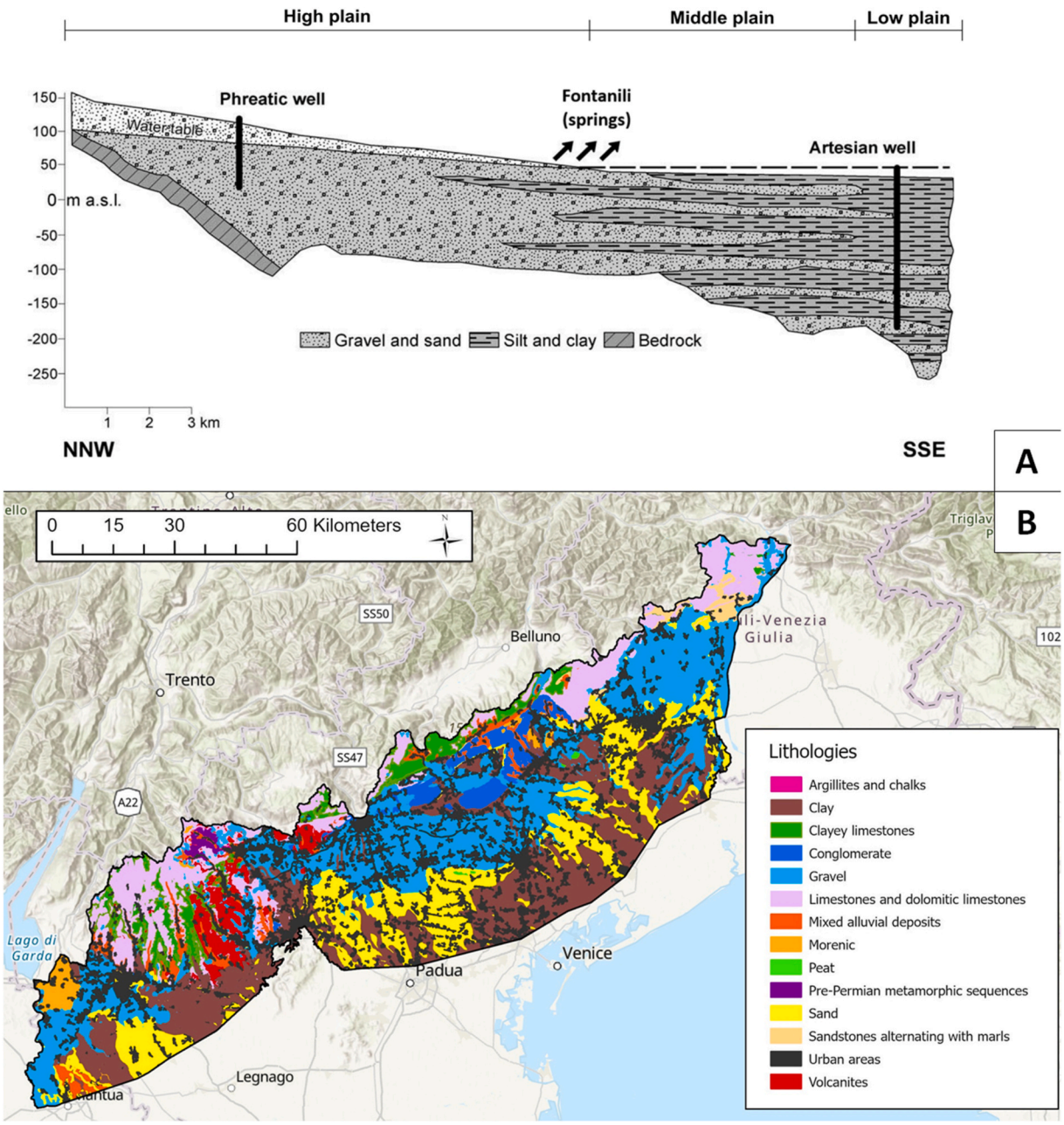


Fig. 2. Conceptual cross section of the Venetian-Friuli plain (Fig. 2a; modified from Piccinini et al., 2016) and lithological map of the study area (Fig. 2b).

The balance domain, shown in Fig. 1, covers an area of approximately 8700 km^2, primarily including the Veneto region but also extending into parts of the Lombardia and Friuli-Venezia Giulia regions. A simplified map of the distribution of surface lithology within the study area, compiled from soil maps of the Veneto, Friuli-Venezia Giulia, and Lombardia regions, is shown in Fig. 2b. This lithological map was integrated with urban areas obtained from the Corine Land Cover 2018 project (CLC, 2018; European Union's Copernicus Land Monitoring Service, 2018), as these impermeable surfaces significantly influence infiltration processes.

3. Methods

3.1. Hydrogeological balance

The method used to describe the quantitative status of the groundwater resources in the study area is hydrogeological balance, which requires the definition of a spatial domain as well as the identification of a temporal domain to evaluate the total inflows and outflows. The time interval considered for this balance covers 13 years, from 2010 to 2022.

Hydrogeological balance is based on the principle of mass conservation:

$$\sum IN = \sum OUT \pm \Delta S \tag{1}$$

where:

- IN = inflows;
- OUT = outflows;
- ΔS = variation in groundwater storage.

Equation (1) can be explained by specifying its main local components:

$$I_{NAT} + I_{ART} + DI_{RIV} + DI_{ART} + GW_{IN} = DR_{RIV} + DR_{ART} + GW_{OUT} + GWE_{OUT} \pm \Delta S \quad (2)$$

where:

- I_{NAT} = natural infiltration;
- I_{ART} = artificial infiltration;
- DI_{RIV} = river dispersion;
- DI_{ART} = artificial channel dispersion;
- GW_{IN} = groundwater inflow;
- DR_{RIV} = river drainage;
- DR_{ART} = artificial channel drainage;
- GW_{OUT} = groundwater outflow;
- GWE_{OUT} = exported groundwater.

Hydrogeological balance was employed to evaluate the sustainability of water use, in conjunction with the analysis of precipitation and groundwater level time series. Under natural conditions, long-term time series analyses are expected to reveal no significant changes in water storage. However, since human activities can substantially alter this balance, a central objective of this study is to quantify such changes. Variations in water storage (ΔS) can be positive if water tends to accumulate or negative if water resources are depleted.

The estimation of the parameters of this regional model is inherently subject to uncertainties, and it is important to provide information on the accuracy of the estimates. However, for assessing uncertainty in a regional-scale study, a classical quantitative uncertainty analysis is not suitable, as it focuses solely on numerical parameters and does not account for unquantifiable uncertainties (Van der Sluijs et al., 2005). These types of uncertainties include the underlying assumptions, the validity of the conceptual model, and the nature of the available data. In the present case, it is considered appropriate to use qualitative descriptors to provide information on the reliability of the data and the procedures employed to obtain specific estimates rather than performing a traditional uncertainty analysis that might yield misleading or uninformative results. Accordingly, a pedigree matrix (Table 1) based on the approach of Weidema and Wesnæs (1996) was employed and adapted to the data quality criteria considered appropriate for regional-scale analysis. The quality indicators adopted in this study integrate information on both the quality of the original data and the robustness of the methods selected to derive the estimates. The following indicators were considered:

- reliability of the data source and acquisition methods, reflecting the quality of the original data;
- spatial coverage in terms of the extent and density of measurement points, reflecting the spatial representativeness of the data;
- temporal coverage in terms of the frequency, continuity, and duration of measurements, reflecting the temporal representativeness of the data;
- consistency of the data, reflecting the homogeneity and comparability of measurements across different areas and the possible integration of heterogeneous information from multiple sources;
- method robustness, in terms of the reliability of the approach used to derive water volumes, reflecting the presence of significant assumptions and simplifications, as well as the need for complementary data.

For each indicator, scores range from 1 to 5, with lower values corresponding to higher data quality and methodological robustness. In cases where multiple types of data were used to estimate a parameter, the indicator score was assigned on the basis of the lowest data quality, following a conservative approach. These scores are not used to derive an overall reliability score for a parameter, as the relative importance of each indicator may vary depending on the weight of the underlying assumptions. Instead, the assigned scores serve as semi-quantitative

Table 1
Pedigree matrix with 5 indicators for the qualitative evaluation of the hydrogeological balance term estimates.

Indicator/ Score	1 (High quality)	2 (Good quality)	3 (Moderate quality)	4 (Limited quality)	5 (Low quality)
Data reliability	Data from monitoring measurements, obtained with standard procedures and validated	Data from measurements with standard protocols, generally trustworthy but with minor uncertainties	Data obtained from reports, with limited documentation on accuracy or measurement procedures	Data derived from indirect methods	No direct measurements; values entirely assumed or inferred without empirical support
Data spatial coverage	Numerous and well distributed data, high spatial representativeness	Sufficient number of well-distributed data	Limited number of data, reasonably distributed	Sparsely distributed or spatially clustered data	No data available within the study area; estimates based on external information or assumptions
Data temporal coverage	High-frequency measurements, covering almost the entire study period	High-frequency measurements covering only part of the study period, or low-frequency periodic measurements	Data based on theoretical, stationary, or mean values (e.g., concession rates)	Isolated or occasional values	No data available for the study period; estimates based on data from earlier periods or on assumptions
Data consistency	Highly consistent and homogeneous data, fully comparable even when from different sources	Generally consistent and reasonably comparable data, with minor differences among sources	Moderately heterogeneous data with noticeable differences among sources	Highly heterogeneous and only partially comparable data when derived from different sources	Single data source or only conceptual assumptions, with no possibility of comparison
Method robustness	Widely applied and validated method, based on direct measures or physically based formulations	Commonly adopted method, simplified with minor assumptions	Simplified approach, dependent on conceptual assumptions and indirect relationships	Simplified approach largely based on conceptual assumptions, supported by a limited number of data.	Estimates derived using an indirect method entirely based on assumptions

indicators, providing a relative measure of confidence and highlighting areas of greater uncertainty. The matrix thus constitutes a practical tool for framing evaluations on the basis of expert judgment and communicating the reliability of results.

3.2. Inflow components

3.2.1. Natural infiltration (I_{NAT})

A GIS-based analysis was performed to upscale the climatic data recorded at the weather monitoring stations to evaluate natural infiltration (INAT). Natural infiltration refers to the portion of rainfall that recharges the groundwater and was calculated on the basis of the classic hydrological balance equation:

$$P - AET_{RP} = EP = I_{NAT} + SR \tag{3}$$

where:

- P = precipitation;
- AET_{RP} = rainfall-related actual evapotranspiration;
- EP = effective precipitation;
- I_{NAT} = natural infiltration;
- SR = surface runoff.

Natural infiltration assessment was carried out in a GIS environment on a raster with 100 × 100 m pixels. Meteorological data were obtained from 220 monitoring stations operated by regional agencies for environmental protection in the Veneto (ARPAV), Friuli-Venezia Giulia (ARPA FVG) and Lombardia (ARPA Lombardia) regions. The daily measurements recorded by the stations were aggregated on a monthly basis, and a monthly average value for each station was obtained to account for the seasonal variability in the meteorological variables. The average monthly values of the parameters in (3) were calculated for the period 2010–2022; subsequently, the monthly water volumes were summed to obtain the average annual value.

The spatial distribution of the average annual precipitation was derived through interpolation using the natural neighbor algorithm (Sibson, 1981). The precipitation was estimated at 11,079.4 M m3/year.

AETRP was estimated using an approach that applies a potential evapotranspiration (PET) formula and, through the introduction of a set of assumptions, enables its adjustment on the basis of the amount of water that is effectively available, thus yielding an actual evapotranspiration (AET) estimate. PET represents the theoretical maximum evapotranspiration that can occur in a given area and reflects only the characteristics of the climatic regime; AET, on the other hand, represents the effective water loss through evapotranspiration, considering the water not only from rainfall but also from other sources in the environment. If the water supply is sufficiently high, the actual evapotranspiration may equal the potential evapotranspiration (Fisher et al., 2011), and this assumption is considered reasonable for many parts of the study area, which are rich in surface water bodies and where extensive irrigation is commonly practiced. Therefore,

$$PET \approx AET = AET_{RP} + AET_{IR} + AET_{SW} \tag{4}$$

where:

PET = potential evapotranspiration;
AET = actual evapotranspiration;
AET_{RP} = rainfall-related actual evapotranspiration;
AET_{IR} = irrigation-related actual evapotranspiration;
AET_{SW} = surface water body-related actual evapotranspiration;

There are several theoretical formulas for calculating potential evapotranspiration. In this analysis, the Penman–Monteith equation proposed by the FAO (Allen et al., 1998) was selected, as it is among the most widely adopted equations for estimating evapotranspiration, and the good availability of meteorological data allowed its application:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)} \tag{5}$$

where

- ET_0 = reference crop evapotranspiration (mm);
- R_n = net solar radiation (MJ/m^2);
- G = heat flow in the subsoil (MJ/m^2);
- T = average air temperature at 2 m above the soil (°C)
- u_2 = wind velocity at 2 m above the soil (m/s);
- e_s = saturated vapor pressure (kPa);
- e_a = effective vapor pressure (kPa);
- Δ = ratio of saturated vapor pressure vs. temperature (kPa/°C);
- γ = psychrometric constant (kPa/°C).

In (5), the reference crop evapotranspiration is calculated, which can be considered equivalent to the potential evapotranspiration; however, a different terminology is adopted to indicate that the resulting evapotranspiration value refers to a standardized reference vegetation surface, as described by Allen et al. (1998). Therefore, the simplification adopted for the calculation of evapotranspiration assumed $AET \approx PET \approx ET_0$. The reference crop is a short grass, such as alfalfa, which under well-watered conditions exhibits a height above the ground of 0.12 m, a resistance of the evapotranspiring surface to vapor flow of 70 s/m and an albedo of 0.23. This assumption represents a significant simplification, and a more detailed assessment would require the derivation of crop coefficients for different plant types. However, these parameters depend on a range of factors, such as plant type, crop growth stage, crop management practices, and local climatic conditions, and this information is difficult to obtain at the regional scale. For this reason, the approximation of actual evapotranspiration (AET) by reference evapotranspiration (ET_0) was adopted as a practical choice (Ashaolu and Iroye, 2018), and in this context, it was considered acceptable, as it reflects conservative conditions. For precipitation, the average monthly values of ET_0 were calculated at each measuring station and spatialized using the natural neighbor method.

Considering that precipitation is the primary source of water lost through evapotranspiration, as it represents a major inflow to the domain, AET_{RP} was calculated by comparing precipitation with potential evapotranspiration according to the following conditions:

$$\begin{cases} if\ P - PET > 0 & AET_{RP} = PET \\ if\ P - PET < 0 & AET_{RP} = P \end{cases} \tag{6}$$

to account for the actual rainfall available to sustain evapotranspiration. In this way, the calculated PET value was assigned to each cell, up to a maximum equal to P; any PET exceeding precipitation was assumed to be compensated by additional water sources, in particular sustained primarily by irrigation and surface water bodies, and therefore assigned to AET_{IR} and AET_{SW} (Sections 3.2 and 3.2, respectively). Part of this evaporative demand may remain unmet in reality; however, it is assumed to represent a minor fraction compared with the portion balanced by irrigation practices and by the widespread presence of surface water bodies, which provide substantial water availability across the study area.

Potential evapotranspiration was estimated at 7707.3 M m^3/year, while the rainfall-related actual evapotranspiration was estimated at 6376.3 M m^3/year.

The effective precipitation (EP) was obtained by subtracting the rainfall-related actual evapotranspiration (AET_{RP}) from the total precipitation, as reported in Equation (3), resulting in a value of 4703.1 M m^3/year. EP can contribute to surface runoff or infiltrate to recharge groundwater; thus, to distinguish between these two

contributions, an approach based on the coefficients of potential infiltration (*CPI*) defined by Civita (2005) was applied, considering the following:

$$I_{NAT} = EP \cdot CPI \quad (7)$$

These coefficients define the tendency of a soil regarding infiltration, with values ranging from 0 to 1, where 0 represents an impermeable substrate and 1 indicates a highly permeable substrate. Therefore, each of the surface lithologies in the study area (Fig. 2b) was associated by similarity with the hydrogeological complexes defined in Civita (2005), assigning the corresponding reference *CPI* value or averaging multiple classes when they were ambiguous. Urban areas were considered completely impermeable because of cementation, resulting in a *CPI* value of 0. Table 2 reports the assigned coefficients of potential infiltration. This approach obviously represents a significant simplification of infiltration dynamics but constitutes a standard method that can be efficiently implemented and reproduced in a GIS environment, and it is particularly suitable for regional-scale analyses when detailed information is not available.

The infiltration value for each pixel of the domain was calculated by applying Equation (7), while the remaining portion of effective precipitation was considered to contribute to surface runoff. Natural infiltration was estimated at 2427.0 M m^3/year, while surface runoff was estimated at 2276.1 M m^3/year. The resulting natural infiltration map is shown in Fig. 3. The quality of the I_{NAT} estimates was based on pedigree matrix criteria; the justifications for the assigned scores are reported in Supplementary Table S1, according to the format proposed by Weidema and Wesnæs (1996). The scores reflect an overall good assessment: data reliability, spatial coverage, temporal coverage, and data consistency were assigned a score of 1, with method robustness being the only criterion to receive a lower score of 3.

3.2.2. Artificial infiltration (I_{ART})

Artificial infiltration (I_{ART}) refers to the water that recharges the aquifers through irrigation practices. In the study area, irrigation is managed by land reclamation consortia (LRCs) or through private self-supply. There are substantial differences between these two operators in terms of both water withdrawal sources and irrigation methods.

LRCs are public entities that manage the distribution of water for irrigation purposes, and the consortium areas can be classified on the basis of the presence of permanent irrigation infrastructure for agriculture. In these structured areas, stable irrigation systems are essential to ensure good agricultural production, whereas in nonstructured areas, irrigation is practiced only during periods of crop demand (emergency irrigation). Structured areas are typical of the high plain, where gravelly and sandy soils have a low water retention capacity, whereas nonstructured areas are characteristic of the low plain, where fine-grained soils generally maintain adequate soil moisture. There are also differences in irrigation methods between these areas: nonstructured areas rely primarily on pressurized systems (mainly sprinkler irrigation), whereas structured areas widely use gravity-based irrigation (mainly surface irrigation) in addition to pressurized systems. The water used for irrigation by the consortia comes mainly from the surface water network. In contrast, private self-supply is widespread in low plain areas, especially where consortia coverage is limited, and primarily involves the use of pressurized sprinkler irrigation methods. The water used for this type of irrigation derives from aquifers and is extracted through pumping wells.

Table 2
CPI values associated with the different lithologies of the study area.

Lithology	CPI
Argillites and chalks	0.15
Clay	0.15
Clayey limestones	0.35
Conglomerate	0.40
Gravel	0.90
Limestones	0.50
Dolomitic limestones	
Mixed alluvial deposits	0.90
Morenic	0.375
Peat	0.15
Pre – Permian metamorphic	0.10
Sand	0.80
Sandstones alternating with marls	0.25
Volcanites	0.25
Urbanized soil	0.00

Different irrigation methods result in different amounts of evapotranspired water: surface irrigation effectively contributes to groundwater recharge through the distribution of large volumes of water, whereas pressurized irrigation systems minimize water application beyond crop requirements and therefore provide only a limited contribution to infiltration. In the study area, these contributions were investigated by Dal Prà et al. (1998) through experimental measurements, and evaporative losses were estimated to be approximately 40% for surface irrigation and approximately 90% for pressurized irrigation. These percentages were subsequently adopted by Fabbri et al. (2016) to estimate irrigation-induced groundwater recharge in a water balance applied to a small portion of the study area, and the same approach was followed in the present study. In areas where pressure irrigation is practiced, the nonevapotranspired water is assumed to fully infiltrate, as it is not provided in a sufficient amount to generate surface runoff. In areas with gravity irrigation, the nonevapotranspired water can contribute to both infiltration and surface runoff, and the partitioning of the volumes was based on the percentage of permeable and impermeable materials present in the areas. The water volumes were provided by the Eastern Alps Water Authority, which collected information on water supplied by the land reclamation consortia in areas with structured irrigation systems, while the self-supplied irrigation volumes consisted of official reported values by the regional authorities. As a result, a total of 1720.5 M m^3/year of water was estimated as supplied for irrigation, with 1318.9 M m^3/year attributed to land reclamation consortia and 401.6 M m^3/year to private self-supply. By applying evapotranspiration percentages based on different irrigation methods, a total irrigation-related actual evapotranspiration (AET_{IR}) equal to 994.6 M m^3/year was obtained, with 633.1 M m^3/year attributed to LRCs and 365.5 M m^3/year attributed to private users. The runoff generated by the LRCs was estimated to be 136.2 M m^3/year, while no runoff was considered to be produced by private self-supply irrigation. The volume of water percolating into the aquifer is 589.7 M m^3/year, of which 549.6 M m^3/year effectively contributes to aquifer recharge, as this represents surface water transfer into groundwater and is attributable to LRCs; for private users, 40.1 M m^3/year is estimated to reinfiltrate into the subsoil from which it was extracted. Since the water used by private users is extracted from groundwater resources, to calculate the net contribution of irrigation to aquifer artificial recharge (I_{ART}), it was necessary to subtract the extracted groundwater volume (401.6 M m^3/year) from the infiltrated volume (589.7 M m^3/year), resulting in an effective contribution of 188.1 M m^3/year. A graphical representation of the results of this analysis is provided in Fig. 4. The rationale for the scores attributed to the quality of the I_{ART} estimates is detailed in Supplementary Table S2: spatial and temporal coverage received ratings of 1 and 2, respectively; data reliability and data consistency both scored 3, whereas method robustness received the lowest rating of 4.

3.2.3. River dispersion (DI_{RIV}) and artificial channel dispersion (DI_{ART})

In the study area, surface water bodies play a fundamental role in the hydrogeological balance and exchange significant amounts of water with the aquifer. In the high plain, where the main alpine rivers flow, significant dispersion (DI_{RIV}) phenomena occur, allowing important recharge of the unconfined aquifer. In addition to the contributions of

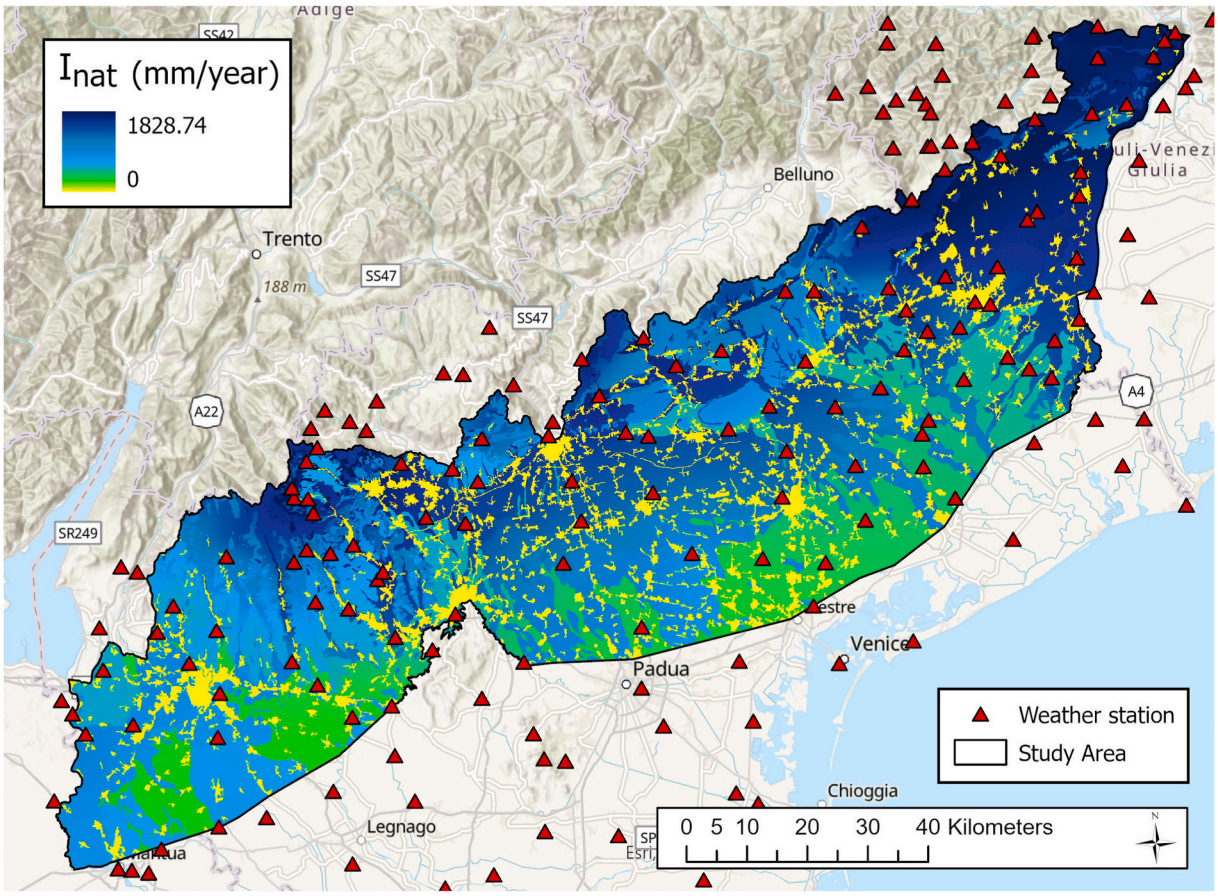


Fig. 3. Spatial distribution of natural infiltration in the domain.

natural watercourses, the artificial channel network plays a primary role in interactions with groundwater. The water diversions in the high plain for electro-irrigation purposes cause dispersion during water transport and feed a dense network of secondary channels that allow water to infiltrate (DI_{ART}). For these reasons, the decrease in river discharge in the high plain is related to both natural river dispersion and artificial channel dispersion ($DI_{TOT} = DI_{RIV} + DI_{ART}$). Given the high water volumes associated with these phenomena, achieving an accurate hydrogeological balance requires their estimation, which is possible only through a deep understanding of surface water dynamics.

To study the interaction between groundwater and surface water, it was necessary to reconstruct the hydraulic schemes of each major river system within the domain (Fig. 1) and assess the inflows and outflows that occurred through natural watercourses, artificial channels, intake structures, discharge points, and hydroelectric plants. There are 17 watersheds identified within the study area, each named after the main watercourse with which they are associated. Monitoring station data and flow rate estimates from unpublished technical reports allowed us to evaluate the river flow rates, and subsequently, by calculating differences in river discharge, it was possible to determine the dispersed and drained water volumes. There are 83 hydrometric stations within the study domain, and they are unevenly distributed among the different watersheds (Fig. 1). Most stations only provide water level data for flood warning purposes and are not equipped with official rating curves. Consequently, discharge volumes were computed using available flow data for 22 stations, whereas for the remaining stations, rating curves were reconstructed where a sufficient number of point discharge measurements was available. In addition, to estimate drainage and dispersion within the study domain, it was necessary to reconstruct the discharge of each main water body at the domain inflow, spring zone, and domain outflow. Where suitable measurement stations were lacking, information from technical reports was used, or estimates were made on the basis of dispersion and drainage coefficients from adjacent areas. The values of the DI_{RIV} and DI_{ART} obtained for each of the river systems are reported in Table 3, while Fig. 5 shows an example of a reconstructed hydraulic scheme.

This analysis led to the estimation of a river dispersion of 4957.2 M m^3/year, which does not account for the actual evapotranspiration from surface water bodies (AET_{SW}), estimated using Equation (4) as 336.3 M m^3/year. Therefore, the net contribution of DI_{RIV} was 4620.9 M m^3/year, while DI_{ART} amounted to 2708.9 M m^3/year. The scores attributed to the quality of the DI_{RIV} and DI_{ART} estimates are documented in Supplementary Table S3; spatial coverage and method robustness received ratings of 2, data reliability and temporal coverage both scored 3, and data consistency received a rating of 4.

3.2.4. Groundwater inflow (GW_{IN})

Groundwater inflow represents the contribution to the hydrogeological budget of the mountain rocky aquifers from the northern boundary. Owing to the lack of direct measurements and the complexity of the system, estimating this component is particularly challenging. As in the approach adopted by Fabbri et al. (2016), the only viable method for quantifying this inflow was through indirect estimation, based on the closure of the hydrological budget. Consequently, its evaluation is presented and discussed in the results section of this study. With respect to this parameter, in the absence of any available information, a value of 5 was assigned to all pedigree matrix quality indicators, except for the method robustness, which was assigned a value of 4, since the use of the water balance to derive unknown terms is a well-established approach, despite the assumptions involved (Supplementary Table S4). To assess the acceptability of the estimate, it was compared with the groundwater outflows (GW_{OUT}), assuming that an acceptable result should be within

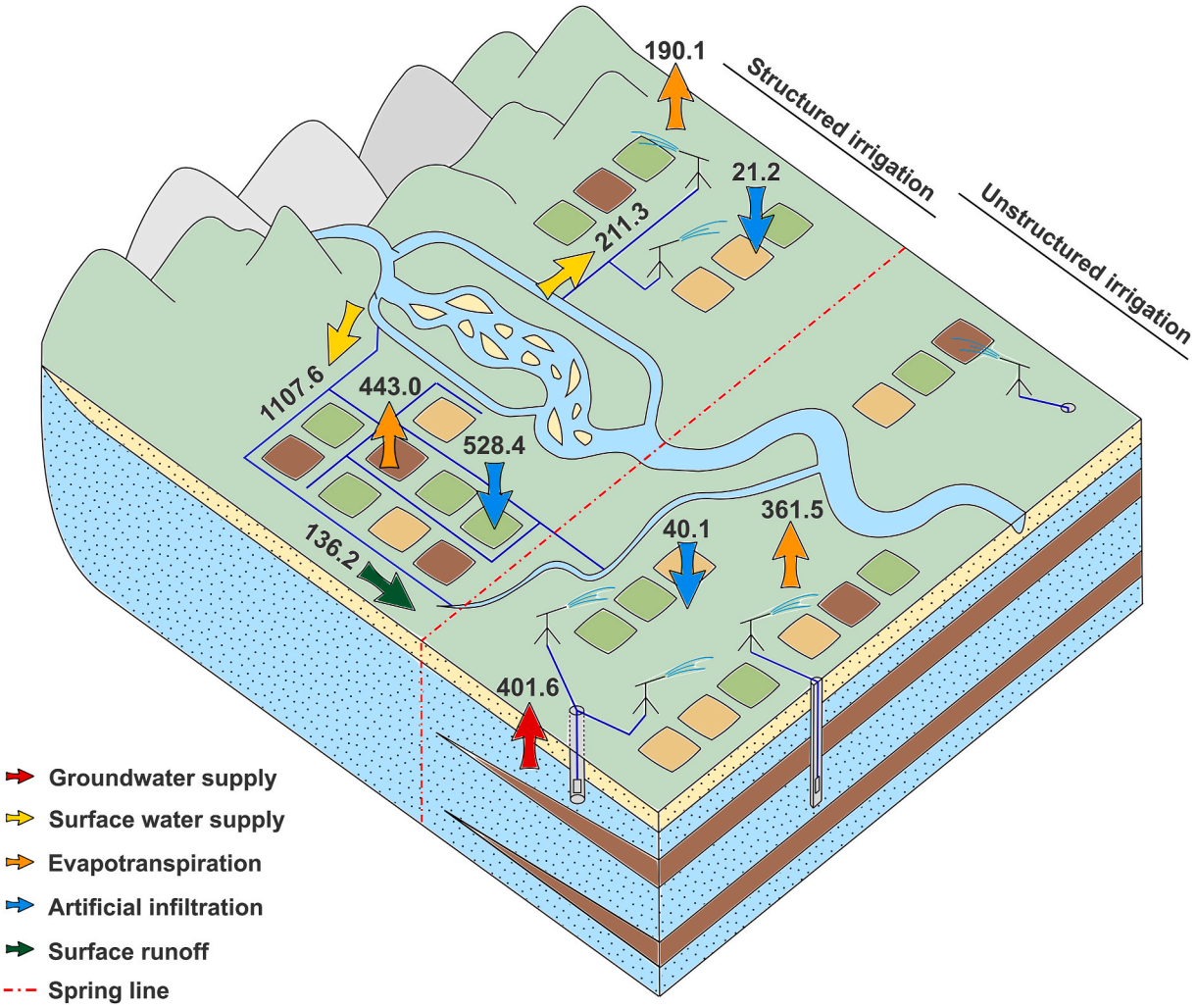


Fig. 4. Hydrogeological budget components related to irrigation, in millions of cubic meters per year.

Table 3
Results of the calculations of river dispersion, artificial dispersion, and total drainage for each watershed in the study area.

Watershed	DI_{RIV}	DI_{ART}	DR_{TOT}
Mincio	156.5	-	232.0
Risorgive Veronesi	-	116.6	505.1
Adige	18.1	507.0	485.3
Togna-Fratta	-	-	67.8
Agno-Gua'	131.2	2.2	150.9
Astico-Bacchiglione	285.0	122.3	941.7
Brenta	578.4	723.9	911.6
Muson dei Sassi	136.6	-	102.3
Tergola	-	-	146.1
Marzenego	-	-	32.7
Dese-Zero	-	-	109.3
Sile	-	538.3	1696.8
Piave	1934.1	94.9	1216.3
Pianura tra Piave e Livenza	-	-	216.7
Livenza	525.1	603.7	1286.0
Lemene	-	-	1093.3
Tagliamento	1192.2	-	-
TOTAL	**4957.2**	**2708.9**	**9193.9**

the same order of magnitude.

3.3. Outflow components

3.3.1. Exported groundwater (GWE_{OUT})

The analysis of water uses in the study area involved extensive data collection on pumping wells, which were classified into 4 categories on the basis of their purpose of use: industrial, irrigation, domestic, and water supply wells. Each of these categories contributes differently to the hydrogeological balance.

Groundwater extracted by water supply wells (GWE_{OUT}) was considered an outflow, as it is removed from the domain through consumption or through pipes that carry it outside the domain areas. In the study area, withdrawals for drinking purposes occur in the high and middle plains, where aquifers have more favorable hydrogeological properties and better quality; subsequently, the water that is not consumed is transported by water supply companies to lower plain areas, where withdrawals generally do not occur. This system operates within the framework of the Italian Integrated Water Service (Servizio Idrico Integrato, SII), the organizational framework responsible for managing the entire potable water supply chain, from abstraction to distribution, wastewater collection and treatment. Within the study area, groundwater is currently withdrawn through approximately 750 wells managed by 14 SII operators. The water volume extracted by the water supply wells was 542.0 M m^3/year on the basis of the withdrawal data provided by the water supply companies. As reported in Supplementary Table S5, the GWE_{OUT} estimates were assigned good quality scores: data reliability, spatial coverage, and data consistency

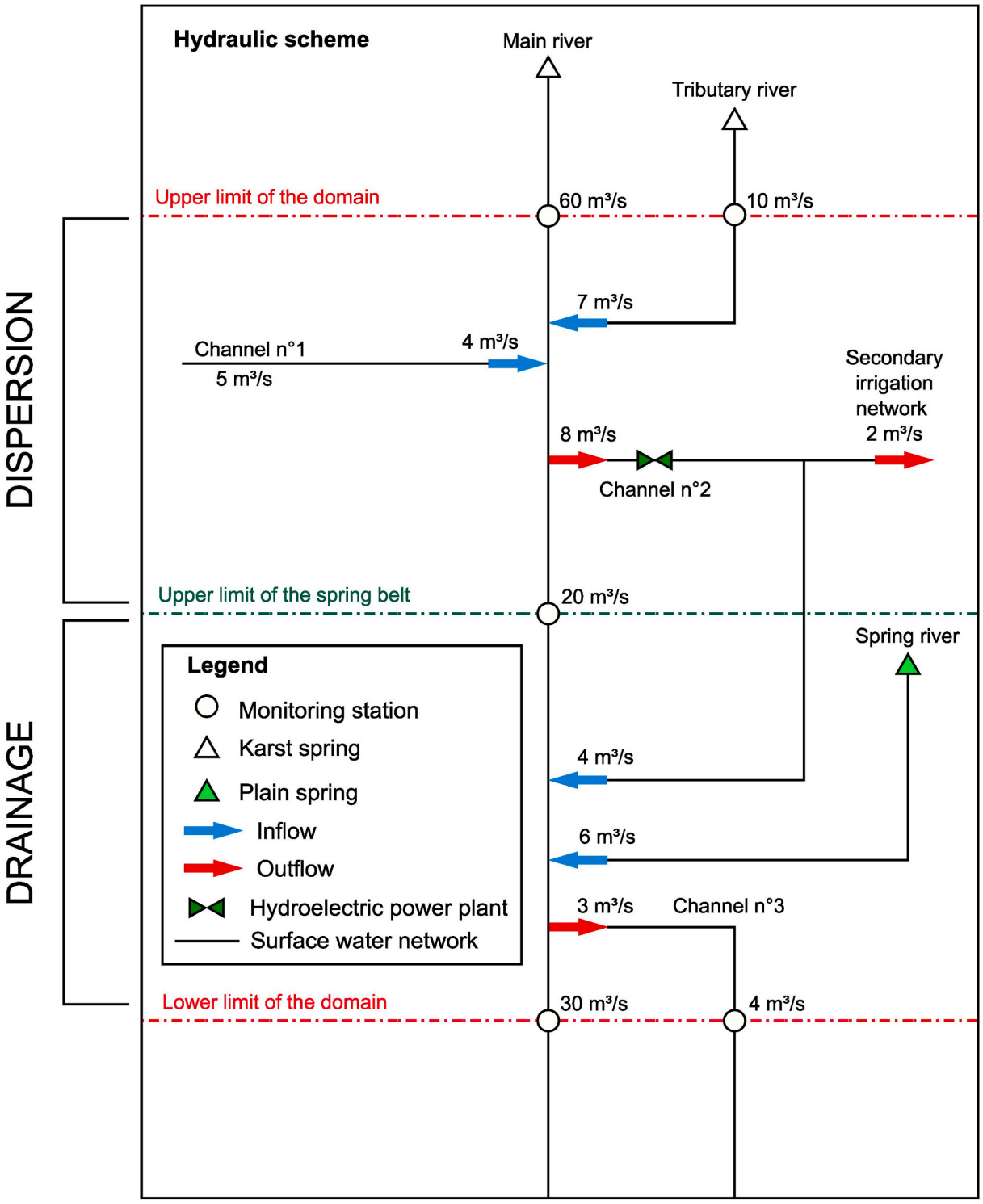


Fig. 5. Schematic example of a reconstructed hydraulic scheme.

received a rating of 1; method robustness scored 2; and temporal coverage received the lowest rating of 3.

3.3.2. *Artificial drainage (DR_{ART})*

In the study area, private wells represent a significant component of the hydrogeological budget. Many of these have mainly industrial and domestic uses, but wells are also used for other purposes, such as livestock, sanitary, and green area irrigation.

Water that is extracted from private wells and not lost during use is discharged into the surface network. In addition, along the spring belt, residents commonly use free-flowing artesian wells, which are left to discharge groundwater into the surface network. Therefore, the groundwater exploited by private wells was considered groundwater transferred from the aquifers to the surface drainage network (DR_{ART}).

Industrial wells, which are licensed to private operators for productive activities, consist of approximately 1500 wells registered within the domain. For these wells, the authorized withdrawal rates (either maximum or average) are available from concession records, and the

volume of water extracted by these wells was found to be 155.1 M m^3/year. Domestic wells, on the other hand, have long posed the greatest challenge for water balances in the study area, as they are often old or unregistered wells and are not included in any comprehensive database. However, since the volumes extracted from domestic wells constitute important hydrogeological balance parameters, they were necessarily estimated. For the Friuli-Venezia Giulia area, the volumes were derived from the regional hydrological budget (Zini et al., 2011). For the Veneto area, this estimate was based on data from the Italian National Statistics Institute (ISTAT, 2021), which allowed the determination of the number of households not reached by the integrated water service of a municipality. In the middle-low plain, such households were assumed to be supplied with water from free-flowing wells with a flow rate of 0.74 L/s, which is consistent with a well 25 mm in diameter. In the high plain, the average water demand per capita, estimated at 93.44 m^3/year on the basis of ISTAT data for northern Italy (ISTAT, 2022), was multiplied by the number of inhabitants not served by the integrated water service. The volumes from these estimates were aggregated with those from wells for other purposes, given the variety of possible uses, resulting in a net abstraction of 88 M m^3/year in the high plain and 977 M m^3/year in the middle and low plain. Along with water from industrial wells, these volumes were considered to flow entirely into the surface water network, with consumption assumed to be negligible, resulting in a total estimation of artificial drainage of 1220.1 M m^3/year. The quality scores assigned to DR_{ART} estimates, documented in Supplementary Table S6, reflect relevant limitations, since spatial coverage, temporal coverage, and data consistency all scored 3, whereas data reliability and method robustness received a rating of 4.

3.3.3. River drainage (DR_{RIV})

In the middle and low Venetian plains, surface waters generally tend to drain groundwater, collecting flows from spring sources and through water exchanges along the riverbed (DR_{RIV}). As previously described for the study of dispersion phenomena, hydraulic schemes were used to study drainage phenomena. In this case, the observable increase in river discharge in the middle–low plain is also related to artificial drainage (DR_{ART}), as water extracted for human activities is transferred into the surface water network. For this reason, it was only possible to reconstruct the total drainage (DR_{TOT}) for each river basin, as the measured flows include both artificial and natural drainage components. However, with an estimate of the artificial drainage available, it was possible to derive the river drainage ($DR_{RIV} = DR_{TOT} - DR_{ART}$), which was estimated at 7973.8 M m^3/year. The results of the analysis of the drainage of the watersheds in the study area are reported in Table 3. The quality scores assigned to DR_{RIV} estimates, detailed in Supplementary Table S7, reflect overall moderate quality: spatial coverage received a rating of 2, and data consistency received a rating of 4, while data reliability, temporal coverage, and method robustness all scored 3.

3.3.4. Groundwater outflows (GW_{OUT})

Groundwater outflows (GW_{OUT}) represent the water flows that exit the domain by moving through the confined aquifers of the middle and low plain along the southern boundary of the study area. A detailed study was conducted on a smaller area within the domain, the Venice Lagoon Basin Council zone, in Fabbri et al. (2016). The study estimated a total groundwater flow of 442.0 M m^3/year, resulting in a groundwater outflow coefficient of 22.1 M m^3/year per km. The GW_{OUT} estimate in the present work was based on the previous study results, adjusting the groundwater outflow coefficient per km of length according to the hydrogeological properties of the materials at the lower boundary of the domain, which is located further south and is composed of materials with lower permeability. Along this boundary, the presence of aquifers was considered for a total thickness of approximately 100 m, which is consistent with the stratigraphy; the hydrogeological properties considered included a hydraulic gradient of 0.12% typical of the plain area, an effective porosity of 15%, a hydraulic conductivity of 10^{-3} m/s, and a flow velocity of 1 m/day. As a result, a groundwater outflow coefficient of 5.5 M m^3/year per km was obtained. By applying this coefficient to the length of the lower boundary of the domain, which is 180 km, a value of 1000.0 M m^3/year was estimated for groundwater outflow. The quality scores assigned to the GW_{OUT} estimates (Supplementary Table S8) highlight the need for further investigation of confined aquifers: temporal coverage received the best rating of 3, whereas data reliability, spatial coverage, and method robustness all scored 4, and data consistency received the lowest rating of 5.

3.4. Variation in groundwater storage (ΔS)

The difference between estimated inflows and outflows indicates an imbalance in the hydrogeological budget during the period 2010–2022. A potential way to explain the observed negative imbalance is to associate this term with the two unassessed parameters in the water budget equation, specifically groundwater inflows from mountain rocky aquifers (GW_{in}) and storage variation (ΔS). The analysis of precipitation and groundwater level time series represented the first step in approaching the estimation of water storage variation, considering that previous studies conducted in the Veneto region have already identified a decline in groundwater levels (Meggiorin et al., 2021; Schiavo, 2024). Furthermore, this analysis can provide insights into whether the observed variation may be linked to climate change (i.e., a reduction in precipitation) or to groundwater overexploitation.

Trend analysis was carried out using data from 185 meteorological rainfall stations and 100 groundwater monitoring wells operated by regional environmental protection agencies. A preliminary step involved addressing the issue of missing data, a common challenge in the analysis of long-term monitoring datasets, by using a machine learning approach implemented through the miceRanger package (Wilson, 2021) in the R software environment (R Core Team, 2025). This method is based on multiple imputation by chained equations (MICE) with random forests. Multiple imputation allows the estimation of missing values while accounting for the uncertainty associated with the imputation process; the chained equation procedure involves an iterative regression process in which each variable with missing data is imputed conditionally on the others. The quality of the imputations produced by the miceRanger package was evaluated by analyzing several characteristics of the imputed data. The distributions of observed and imputed data were compared, and boxplots of correlation coefficients (e.g., Pearson, Spearman, and Kendall), calculated between multiple imputations at each iteration, were constructed. Another diagnostic involved analyzing the evolution of the mean and standard deviation across iterations for each imputation. Additionally, the out-of-bag (OOB) R^2 was calculated. The OOB R^2 is a measure of the predictive performance of a regression model computed using out-of-bag predictions within the bootstrap aggregating (bagging) framework. In this approach, each base model is trained on a bootstrap sample of the original dataset (in-bag data), while the observations not included in that sample are referred to as out-of-bag (OOB) data. The OOB R^2 evaluates how well the OOB predictions explain the observed variability in the response variable, similarly to the classical R^2, but uses only OOB predictions to reduce overfitting. In this application, precipitation gaps were estimated using the entire set of rainfall stations, and groundwater level gaps were estimated using the complete set of monitoring wells. The R code employed is included in the supplementary materials, alongside all the graphs and metrics computed for the rainfall data imputation.

The trend analysis employed the modified Mann–Kendall test (Hamed and Rao, 1998), implemented in the modifiedmk R package (Patakamuri and O'Brien, 2021). This allowed the detection of statistically significant trends while accounting for data autocorrelation, which is particularly relevant for groundwater level time series. Among the 185 rainfall stations, only 4 exhibited a statistically significant decreasing trend in annual precipitation; these four stations are located outside the

study domain in the Alpine region. This suggests that no clear evidence of climate-induced change in annual rainfall volume was observed for the analyzed period. In contrast, 16 out of the 100 groundwater level stations showed a significant negative trend, with an average decrease estimated by Sen's slope at 0.147 m/year; the remaining 84 stations did not exhibit any statistically significant trend. The results of the trend analysis for the stations that exhibit a significant trend are reported in Table 4.

These results allow the assessment of the quantitative status of water bodies (SNPA, 2017; ARPAE, 2019). To quantify the variation in groundwater storage, a simplified procedure was adopted, which was based on the water table fluctuation method (WTF; Prasad and Rao, 2018; Meza-Gastelum et al., 2022; Brookfield et al., 2024), with the following assumptions:

$$\Delta S = Sy \cdot A \cdot \Delta h \tag{8}$$

where:

- Sy = specific yield (−);
- A = area (m^2);
- Δh = drawdown (m).

Therefore, the Sen's slope values of the groundwater levels were spatially interpolated using the natural neighbor algorithm, resulting in a spatial representation of the drawdown across the study area. This approach introduces the assumption of spatial continuity of unconfined aquifers. While this assumption is consistent with the conceptual model in the upper plain, it is less justified in the lower plain, where unconfined aquifers are thinner and often laterally discontinuous. Owing to the lack of monitoring data for confined aquifers in the middle and lower plains, piezometric declines could be documented only for unconfined systems. Consequently, a conservative approach was adopted to extrapolate the calculated drawdown across the entire study area. As a consequence, the estimated ΔS value is expected to represent an overestimation; however, it provides meaningful information on the plausible range of this quantity. Once a drawdown value was assigned to each 100 × 100 m grid cell, it was multiplied by the cell area and the specific yield to estimate the resulting reduction in water volume. The values of specific yield were derived from Fetter and Kreamer (2022): an average value of 23% was assigned to the high plain area, corresponding to medium gravel, whereas a value of 21% was used for the low plain area, which was representative of fine sand. Typical values from the scientific literature were adopted because the datasets from which well information was derived lack hydrogeological parameters, such as hydraulic conductivity, specific yield, or specific storage. This information is often archived by well owners in technical documents and reports, which are frequently still in paper format. Given the complexity of determining the spatial distribution of storage parameters, in the absence of adequate site-specific data, it was considered appropriate to divide the area into relatively homogeneous zones and assign values on the basis of the available literature. As a result, the change in water storage (ΔS) in the domain was approximately 153.6 M m^3/year. The results of the drawdown interpolation are shown in Fig. 6. In the eastern sector, where there is a greater number of monitoring points, the drawdowns are more concentrated; however, in the western sector, the monitoring points define an area with greater drawdown, which is consistent with current observations in the Adige River Basin. Although the current number of monitoring stations is limited with respect to the extent of the study area, the proposed method is inherently scalable and can be progressively improved as the spatial coverage of piezometric monitoring stations increases. In addition, the analysis of piezometric trends plays a key role in the assessments conducted by public administrations for evaluating the quantitative status of groundwater bodies, as required by the Water Framework Directive; consequently, applying this method proves useful in supporting these evaluations. As reported in Supplementary Table S9, the ΔS estimates reflect accurate but poorly distributed data, which affects the quality of the spatialization: data reliability, temporal coverage, and data consistency all achieved the best rating of 1, whereas spatial coverage and method robustness received the lowest rating of 4.

Table 4
Results of the analysis of the annual time series for the stations exhibiting a significant trend. Sen's slope is expressed in m/year for groundwater level monitoring stations and in mm/year for rainfall monitoring stations.

ID	Monitoring network	Original p-value	Corrected p-value	τ	Sen's slope
P1	Rainfall	0.024	0.024	−0.48	−0.036
P2	Rainfall	0.16	0.037	−0.30	−0.054
P3	Rainfall	0.076	0.006	−0.38	−0.050
P4	Rainfall	0.076	0.016	−0.38	−0.068
L1	Groundwater level	0.003	0.003	−0.77	−0.14
L2	Groundwater level	0.002	0.08	−0.8	−0.46
L3	Groundwater level	0.024	0.024	−0.49	−0.03
L4	Groundwater level	0.017	0.017	−0.51	−0.05
L5	Groundwater level	0.006	0.006	−0.59	−0.12
L6	Groundwater level	0.044	0.006	−0.44	−0.09
L7	Groundwater level	0.024	0.024	−0.49	−0.05
L8	Groundwater level	0.006	0.006	−0.59	−0.17
L9	Groundwater level	0.044	0.044	−0.79	−0.46
L10	Groundwater level	0.044	0.044	−0.44	−0.17
L11	Groundwater level	0.044	0.044	−0.44	−0.15
L12	Groundwater level	0.024	0.024	−0.49	−0.12
L13	Groundwater level	0.009	0.009	−0.56	−0.17
L14	Groundwater level	0.024	0.000	−0.54	−0.14
L15	Groundwater level	0.009	0.009	−0.56	−0.21
L16	Groundwater level	0.024	0.024	−0.49	−0.12

4. Results and discussion

The analyses carried out in this study supported the estimation of the inflows and outflows of the hydrogeological water budget in Equation (2). Inflows amount to 2427.0 M m^3/year from natural rainfall infiltration, 188.1 M m^3/year from artificial infiltration, 4620.9 M m^3/year from river dispersion, and 2708.9 M m^3/year from artificial dispersion. The outflows are 7973.8 M m^3/year from river drainage, 1220.1 M m^3/year from artificial drainage, 542.0 M m^3/year from extraction by water supply companies, and 1000.0 M m^3/year from groundwater outflow. The negative variation in groundwater storage was estimated at 153.6 M m^3/year. Once these values were obtained, all terms of the hydrogeological budget were estimated, except for groundwater inflows (GW_{IN}), which were indirectly inferred to close the balance, yielding a value of 637.4 M m^3/year. The GW_{IN} value obtained was considered acceptable and was comparable to the GW_{OUT} value. The hydrogeological budget results (Fig. 7) provide insight into the distribution of recharge and withdrawals; quantify the relative contributions of natural and anthropogenic factors; and thereby identify where climate change, exploitation, and management interventions may most significantly influence the sustainable use of resources. The procedures adopted to achieve these results, including spatial maps, hydraulic schemes and simplified estimation methods, further enable the balance to be scaled

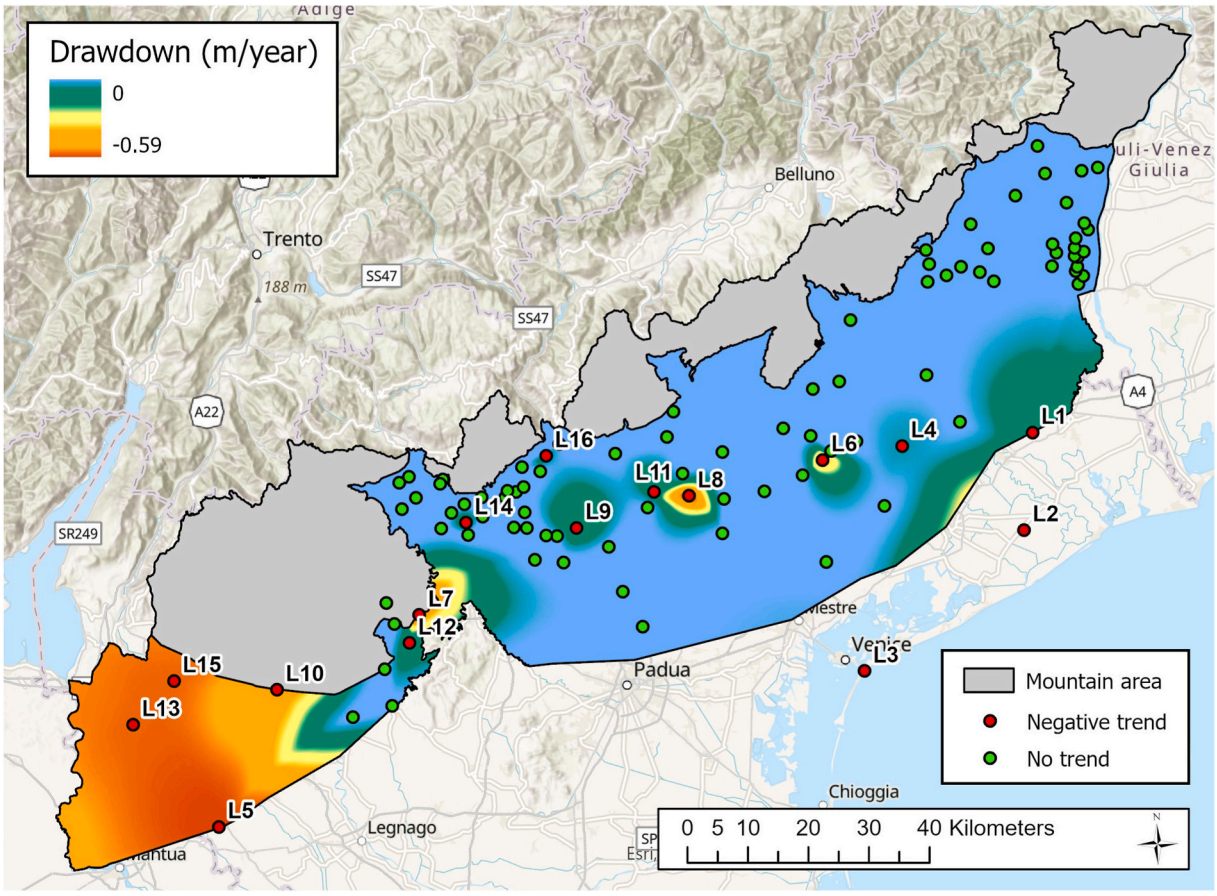


Fig. 6. Map of the annual average drawdown obtained by spatializing the results of the groundwater trend analysis.

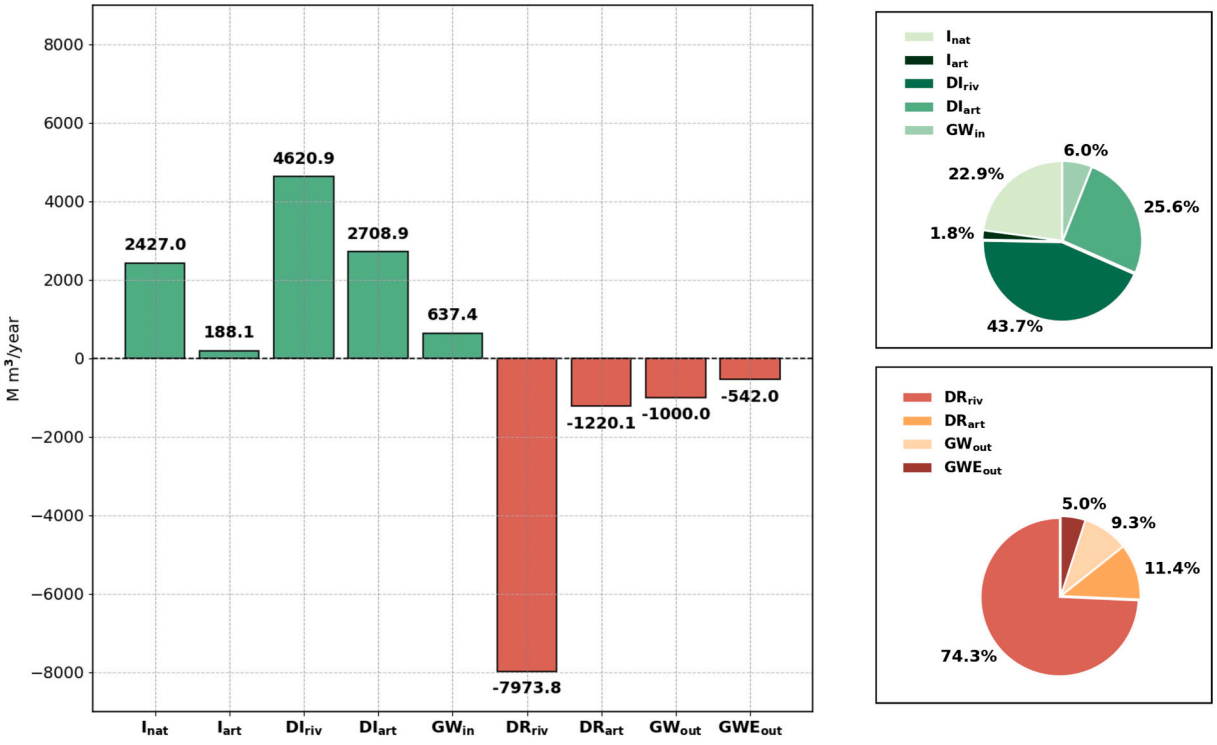


Fig. 7. Histogram of the principal components of hydrogeological balance. The green bars represent the inflow components, whereas the red bars represent the outflow components.

down to the subbasin scale, where management interventions are ultimately implemented.

The quality of the different components of the hydrogeological balance was evaluated using the five indicators of the pedigree matrix. Table 5 presents the overall results of this analysis, highlighting aspects that could be further refined in future work. In particular, with respect to the current monitoring network, the spatial coverage of groundwater level monitoring stations and hydrometric stations should be increased, and the latter stations should be equipped with rating curves. Hydrometric stations may be placed along the spring belt, at the point where river behavior transitions from loss to gain, which would be useful for the calculation of dispersions and drainage from hydraulic schemes. Another potential improvement for future work would be the use of actual measured flows instead of mean or concessioned flows in the case of irrigation diversions by consortia, hydroelectric withdrawals, or water extracted from supply wells; however, these values are difficult to obtain because of commercial confidentiality. In addition, in the study area, further investigation of the groundwater system is needed, as despite the existence of a well-established conceptual model, the detailed structure and hydrogeological properties of the aquifers remain largely unknown, except in areas associated with the water supply company well fields. Targeted studies could also be conducted to improve the estimation of specific parameters, as outlined in Table 5. These recommendations align with the objective of this model to support the activities of the Eastern Alps Water Authority, an institution that aims to continuously update information for assessing the quantitative status of surface water and groundwater and implementing dedicated projects, in accordance with the Water Framework Directive. In this framework, the level of detail achieved in the present study is considered well suited to define the constraints for the future development of a numerical groundwater flow model. The calibration of such a model based on both water budget components and piezometric levels would further consolidate the robustness of the hydrogeological balance presented here.

The results obtained are consistent with the volumes circulating in the study area. To further validate this hydrogeological balance, a comparison was carried out with the results of the national-scale hydrological/hydrogeological balance BIGBANG 8.0, proposed by ISPRA (Braca et al., 2023). The ISPRA balance for the area covered in the present study reported a precipitation volume of 11,297.4 M m^3/year, which is in good agreement with the 11,079.4 M m^3/year estimated by this study. Greater differences were found in the evapotranspiration value, which was 5006.7 M m^3/year according to ISPRA and 7707.3 M m^3/year in the present study, because of the different methods used for calculating potential evapotranspiration, namely, the Thornthwaite method (Thornthwaite and Mather, 1955, 1957) and the FAO Penman–Montheit method (Allen et al., 1998). Temperature-based models, such as the Thornthwaite method, tend to estimate lower effective precipitation values than models combining temperature and solar radiation, such as FAO Penman-Montheit, and differences in estimates between these methods are typically greater than 25% (Fisher et al., 2011). The differences in evapotranspiration are reflected in the effective precipitation, which is 6290.7 M m^3/year according to the ISPRA balance and 4703.1 M m^3/year in the present study; in the runoff results, which are 2951.2 M m^3/year and 2276.1 M m^3/year, respectively, and in the infiltration results, which are 3349.6 M m^3/year and 2427.0 M m^3/year, respectively. Both models used the same method to distribute effective precipitation, that is, the *CPI*. For this reason, the subdivision of effective precipitation volumes into effective infiltration and surface runoff was very similar, with 53% infiltration and 47% surface runoff in ISPRA and 52% and 48% in the current study. The two balances produce comparable and consistent results, except regarding the estimation of evapotranspiration, which is always subject to significant uncertainty (especially at this scale).

Comparisons were also carried out with the water balance results reported by Fabbri et al. (2016), who covered a small portion of the present study area, located between the Brenta and Piave Rivers. In this area, the current water balance estimates a river dispersion of 609.2 M m^3/year, which is in good agreement with the value of 570 M m^3/year reported in the previous study. Similar results are found regarding groundwater drainage, both natural and artificial, with 1208.5 M m^3/year in the present analysis and 1302 M m^3/year in the former study. However, differences emerge in the estimation of precipitation-induced infiltration, which was calculated as 232.3 M m^3/year in the present analysis, compared with 380 M m^3/year in the 2016 study. This discrepancy is attributable mainly to the method adopted for estimating actual evapotranspiration: the present study uses a comparative approach based on potential evapotranspiration and available water, whereas Fabbri et al. (2016) applied the Turc equation (Turc, 1954) for direct estimation of actual evapotranspiration. As in the 2016 study, the main groundwater recharge component considered here is related to irrigation, estimated at 600 M m^3/year in the previous study and 830 M m^3/year in the present analysis. This difference may reflect uncertainties in the actual volumes of water used for irrigation, which are often provided as concession flow rates rather than actual flow rates. Nevertheless, the obtained values provide a reasonable estimate of the magnitude of the hydrological budget terms, as supported by comparisons with both larger-scale and smaller-scale models.

A parameter of the hydrogeological balance that requires particular attention is the variation in groundwater storage, as it represents

Table 5
Qualitative evaluation of the reliability of hydrogeological balance parameters.

Parameter/Indicator	Data reliability	Data spatial coverage	Data temporal coverage	Data consistency	Method robustness	Proposals for future improvement
Natural infiltration	1	1	1	1	3	Application of crop coefficients for the estimation of crop evapotranspiration.
Artificial infiltration	3	1	2	3	4	Transition from a lumped to a distributed model, refining the irrigation impacts on recharge.
River dispersion and Artificial dispersion	3	2	3	4	2	Increase in the number of monitoring stations equipped with rating curves; adoption of measured flows rather than concession rates.
Groundwater inflow	5	5	5	5	4	Local-scale analysis of inflows from mountain rocky aquifers to support upscaling.
Exported groundwater	1	1	3	1	2	Acquisition of continuous water meter readings; assessment of leakage losses in water supply pipelines.
Artificial drainage	4	5	3	3	4	Detection of flowing wells and evaluation of their discharge
River drainage	3	2	3	4	3	Increase in the number of monitoring stations equipped with rating curves; adoption of measured flows rather than concession rates.
Groundwater outflows	4	4	3	5	4	Increase in spatial coverage of groundwater level monitoring stations, and detailed assessment of hydrogeological properties of aquifers.
Variation in groundwater storage	1	4	1	1	4	

changes in water resource volume and availability, and it is important to understand the possible causes of these variations. The analyses conducted indicated a decrease in ΔS over the period 2010–2022, which could result from a reduction in inflows, an increase in outflows, or a combination of both. The reduction in inflows may be related to climate change leading to reduced annual recharge, whereas the increase in outflows is associated with groundwater overexploitation. The reduction in inflows could also be attributed to river regulation upstream of the plain; however, this explanation is unlikely, as during the analyzed period, neither the water distribution patterns within the domain nor the reservoir operating behavior changed. Trend analysis using the modified Mann−Kendall test revealed significant negative trends at only 2% of the analyzed rainfall stations, all of which were located outside the study domain, whereas 16 of the 100 groundwater monitoring stations showed significant negative trends. This may suggest that the observed negative variation in groundwater storage is more likely attributable to groundwater overexploitation than to a decrease in rainfall associated with climate change. However, although the total annual precipitation volume did not change, its intra-annual distribution decreased during the autumn season, one of the two main rainy seasons in the area, and spring. This shift may influence aquifer recharge patterns, potentially favoring surface runoff over infiltration during certain periods. Further analysis should be conducted to assess the magnitude of this effect.

Regardless of the primary driver of groundwater depletion, natural recharge and sustainable abstraction cannot be treated as independent components, since any reduction in recharge directly reduces the amount available for sustainable withdrawal; therefore, the present study highlights the need for planning measures to safeguard the quantitative status of groundwater resources. Given that the observed variation in water storage at present is moderate and is attributable mainly to overexploitation, proper water management could effectively mitigate further depletion. Various sustainability strategies can be adopted, which can be categorized into methods for increasing inflows and methods for reducing outflows. Among the former, the following can be included: the establishment of artificial groundwater recharge zones in the unconfined aquifer of the high plain; the diversion of surface waters into the irrigation canal network even during the nonagricultural period; and the prevention of excessive diffusion in the high plain by irrigation methods that minimize water consumption but reduce groundwater recharge through infiltration processes. Among the methods used to reduce outflows, the following can be considered: the identification and closure of flowing wells in the middle–low plain; the increase in users of the integrated water supply service through the extension of the water network; and the expansion of the consortium network to reduce self-supply irrigation from groundwater and promote irrigation from surface water sources. These solutions essentially involve reducing the consumption of valuable groundwater resources and increasing the use of surface water. However, these methodologies must be evaluated while considering other ecosystem services provided by surface waters, such as the prevention of saltwater intrusion and the preservation of natural habitats. Therefore, it is necessary to carry out assessments of minimum vital flow (MVF) and ecological flow (or environmental flow, EF) for rivers. Moreover, groundwater cannot always be replaced by surface water because of issues related to the generally low-quality status of groundwater. Notably, certain groups may oppose river infrastructure projects for different reasons, which may be environmental, political, or administrative.

5. Conclusions

Groundwater resources represent a vital asset for society, both for human consumption and for productive uses, and must be safeguarded to allow their sustainable exploitation. Effective groundwater management requires careful evaluation of the main components affecting aquifer recharge and withdrawal. For these reasons, this article presents a detailed regional-scale hydrogeological budget for a portion of the Veneto-Friulian plain, covering an area of approximately 8700 km^2 and considering the period 2010–2022. The present work bridges the gap between local- and national-scale assessments by focusing on the watershed scale, which coincides with the administrative boundaries of the Eastern Alps Water Authority, the public agency responsible for resource management. Quantification of the main terms of the hydrogeological budget equation makes it possible to identify the components that most significantly affect the availability of water resources. Among the inflows, 43.7% are attributed to river dispersion, 25.6% to artificial channel dispersion, 22.9% to natural infiltration, 6.0% to groundwater inflow, and 1.8% to artificial infiltration. Among the outflows, 74.3% are attributed to river drainage, 11.4% to artificial drainage, 9.3% to groundwater outflows, and 5.0% to exported groundwater. The decrease in water storage accounts for 6.9% of the total volume.

From the analysis reported in this study, the following key findings emerge:

- Most of the water entering the subsurface originates from the dispersion of surface watercourses rather than from direct infiltration of precipitation;
- Aquifer recharge from agricultural activities contributes significantly to the water balance, and it is believed that the transition from surface irrigation to pressurized irrigation may result in a marked reduction in artificial aquifer recharge;
- There is a modest negative variation in storage within the study domain, which is believed to be related primarily to groundwater overexploitation rather than to climate change and can potentially be addressed through sustainable water resource management practices;
- All major components of the water balance were quantified, except for the contribution from mountain rocky aquifers, which was inferred as the residual necessary to close the balance.

All of these statements are supported by the results of the hydrogeological balance and trend analyses. A comprehensive overview of the main characteristics of the study area is provided, particularly through the quantification of the key components of the hydrogeological budget. Therefore, the present study offers a fundamental contribution to the assessment of sustainable groundwater use, as it quantifies natural recharge, identifies the principal users in terms of abstracted volumes, and defines a quantitative basis for targeted management interventions and mitigation measures. The results suggest that, although limited in magnitude, the hydrogeological balance is negative. This condition is particularly concerning in the context of increasing climatic variability, as it reduces the capacity of the system to absorb climatic fluctuations and increases its vulnerability to drought. This is further verified by the recurrent drought episodes that affected the region in 2007, 2012, 2017, and 2022. In this context, the hydrogeological balance serves not only as a diagnostic tool but also as a planning instrument, providing water managers and stakeholders with a robust quantitative framework to design targeted measures and evaluate where reductions or compensatory measures would be most effective.

In addition to providing the values that characterize the study area, this study offers an example of some strategies that can be used to make regional-scale assessments of hydrogeological balance terms. The combination of various techniques, i.e., GIS-based analysis, water use analysis, hydraulic scheme reconstructions, trend analysis, and upscaling of known data, allowed the construction of a solid conceptual model for understanding the regional hydrogeological balance. The adopted approaches proved essential for defining a detailed budget over a large area characterized by datasets that are extensively available yet often incomplete, heterogeneous, and detailed only for certain parameters. In this context, the present study illustrates how hydrogeological budgets can be developed using complementary methodological approaches while emphasizing the importance of clearly justifying estimation methods and transparently communicating their associated reliability,

an aspect that is particularly relevant in data-scarce areas. For this reason, a practical pedigree matrix was adopted to explicitly communicate the model's limitations and to contextualize the authors' expert judgment regarding data quality and the robustness of the estimation methods. This analysis indicates that improving the understanding of certain hydrogeological budget parameters requires dedicated studies to refine the conceptual model, whereas in other cases, the focus should be on enhancing data quality. In this context, critical aspects concern the flow rates extracted from private wells and the discrepancy between the authorized diversion flows for irrigation and the actual volumes withdrawn. In addition, the present study highlights the need to improve the coverage of the piezometric and hydrometric monitoring networks and to equip the latter with appropriate rating curves. These limitations identify the areas where public authorities and research institutions can focus their attention to develop more precise and reliable assessments in the future.

In conclusion, this study offers a robust and effective conceptual model and quantitative estimates of the hydrogeological budget for public agencies in the Venetian Plain, and these estimates can serve as valuable constraints for the water mass balance of future numerical groundwater flow models. This quantification supports public authorities in achieving a fundamental goal in sustainable groundwater management: the ability to reason in numerical terms about the volumes and flows circulating at a regional scale. This is a significant achievement, as discussions about water resources often rely on qualitative assessments rather than clear estimates of the actual quantities involved.

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CRediT authorship contribution statement

Davide Cappellari: Data curation, Formal analysis, Investigation, Writing – original draft. **Roberto Tonucci:** Data curation, Formal analysis, Investigation, Writing – original draft. **Leonardo Piccinini:** Investigation, Methodology, Writing – review & editing. **Andrea Braidot:** Investigation, Supervision. **Alberto Cisotto:** Investigation, Supervision. **Nico Dalla Libera:** Investigation, Supervision. **Paolo Fabbri:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2026.101641.

Data availability

Data will be made available on request.

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