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ORIGINAL ARTICLE

Hydrological imbalance in the veneto-friuli plain (Northeastern Italy): climate change or groundwater overexploitation?

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Abstract

This study presents a regional-scale hydrological balance for the upper and middle Veneto-Friuli Plain in northeastern Italy, covering approximately 8700 km^2. The analysis focuses on the period 2010–2022 and is aimed at quantifying the main recharge and discharge components, assessing the sustainability of water resources, and supporting informed management decisions. Inflows were assessed based on precipitation, surface runoff from rivers and springs, and water imports for human use, whereas outflows included river discharge, actual evapotranspiration, and groundwater withdrawals. Results indicate an annual water imbalance of 232.4 M m^3. This imbalance could be due to either climate change or increased anthropogenic pressures, including groundwater overexploitation. To distinguish between these potential drivers, trend analyses were performed using a modified Mann-Kendall test on both precipitation and groundwater level data. No significant negative trends were observed in annual precipitation records from 185 meteorological stations. In contrast, declining trends were identified in 16 out of 100 monitored piezometers, suggesting that part of the imbalance, estimated at 37.2 M m^3/year, may be attributed to groundwater depletion caused by overexploitation. The remaining 195.2 M m^3/year is likely associated with unquantified groundwater inflow from adjacent fractured-rock aquifers. The findings highlight a substantial human footprint on the regional water cycle and emphasize the need for enhanced hydrological monitoring to reduce uncertainties in water balance estimates. This comprehensive water budget offers critical insights into water origin, use, and sustainability in the region, providing a scientific basis for adaptive and integrated water resource management strategies.

Keywords Hydrological water budget · Water management · Anthropic impact · Veneto-Friuli Plain

Introduction

The quantification of water available for human use and consumption, along with its protection and sustainable management, represents a crucial challenge for both the scientific and policy communities. Since the 1990 s, to address the issue, policies focused on reducing environmental impact and protecting water quality have been pursued and implemented through regulatory frameworks worldwide. Currently, in Europe, the main legislative reference is the Water Framework Directive (WFD; Directive 2000/60/EC; European Parliament and Council 2000), which aims to ensure the good status of surface and groundwater bodies through the protection from pollution and the sustainable management of water resources.

To achieve these objectives, defining and quantifying the components of the hydrological cycle is of primary

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importance, and these can be estimated through the hydrological budget. This method accounts for all water volumes involved in the hydrological cycle within a defined area and time period, describing the main components driving water circulation. The hydrological budget applies the principle of mass conservation to water volumes, allowing the detection of differences between inflows and outflows that may indicate changes in water storage. Identifying such variations is essential for effective water resource management, as the water cycle can be influenced by both natural and anthropogenic factors that significantly affect water availability.

Different approaches to evaluate the water budget exist, starting from analytical water budgets (Mollema et al. 2013; Fabbri et al. 2016; Althoff et al. 2021; Choi et al. 2023; Li et al. 2023; Gebreeyesus et al. 2025) to bidimensional or three-dimensional numerical modeling (Rayburg and Thoms 2009; Tóth et al. 2016; Wen et al. 2013). Numerical models are well-suited for complex and high-resolution studies, as they require substantial data availability and enable the development of management scenarios (Omar et al. 2021; Harik et al. 2023; Amognehegn et al. 2023; Senent-Aparicio et al. 2024). Conversely, analytical water balances, although based on simplified assumptions, offer an effective and easily communicable approach for large-scale analyses, particularly in contexts where data availability is limited or incomplete.

Water budgets can be applied at different scales; however, those aimed at resource management are typically conducted at the regional scale (Claessens et al. 2006; Thompson et al. 2009; Cao et al. 2013), aligning the extent of the study area with that of the governing public authority.

In Italy, the analytical hydrological/hydrogeological budget is beginning to assume greater importance in water management, since a national hydrological model (BIGBANG) was proposed by the Italian Institute for Environmental Protection and Research (ISPRA; Braca et al. 2023), and some Italian regions like Friuli-Venezia Giulia, Piemonte and Lombardia have developed water budgets. However, the development of hydrological budgets is also progressing in other regions, in order to enable the Water Authorities, the public agencies responsible for water management, to comply with the requirements set by the WFD. In particular, water budgets serve as a useful tool to assess the quantitative status of water bodies.

In the Veneto region the issue of water resource assessment has gained increasing importance in recent years due to declining groundwater levels in certain areas (Meggiorin et al. 2021; Schiavo 2024) and the severe drought of 2022. For these reasons, this article presents a regional-scale analytical hydrological budget of the high and middle Veneto-Friuli plain, a highly productive area of Italy characterized by abundant water availability and intensive exploitation of water resources. The period of observation extends over 13 years, from 2010 to 2022, and the study area covers approximately 8700 km^2, stretching from the Mincio to the Tagliamento rivers, representing the first water budget developed for such a large portion of the Veneto region. The interest in quantifying the area's water resources is also evidenced by previous studies conducted in smaller portions of the same region (Fabbri et al. 2016; Gatto et al. 2023).

This water budget enabled the estimation of volumes associated with the various components of the regional hydrological cycle, and the adoption of multiple estimation approaches provided valuable insights into the interactions between human activities and water resources. The results revealed a modest imbalance, which was further explored through trend analyses of precipitation and potentiometric data to determine whether the observed variations could be attributed to anthropogenic pressures or climate change, two of the primary drivers influencing hydrological systems. Identifying the prevailing driver is essential to support more effective and sustainable water resource management (Mikaeili and Shourian 2023).

This imbalance also allowed for the indirect quantification of key components, such as subsurface inflows from adjacent mountainous bedrock aquifers and the actual depletion of groundwater reserves. Moreover, the development of a regional water budget helped to identify the parameters subject to greater uncertainty, indicating where institutional efforts should be directed to enhance existing hydrological monitoring networks.

Study area

The study area is about 8700 km^2 wide and is focused on the Veneto-Friuli plain, but it also includes a part of the Padana plain in the Province of Mantova (Fig. 1). The western limit of the domain is the Mincio River (in the Lombardia Region) and the eastern limit is the Tagliamento River (in the Friuli-Venezia Giulia Region). The northern limit follows the ridges of the watershed inside the domain, and it intersects the hydrometric stations located at the valley outlets. This ensures that the river discharges measured at these stations are equal to the flow rates entering the domain. The southern limit connects and intersects the hydrometric stations on the main rivers in the area, since the domain is crossed by great alpine rivers (e.g. Adige, Brenta, Piave and Tagliamento) and by spring rivers (e.g. Bacchiglione, Sile and Livenza). In this way, as in the northern limit, it was possible to evaluate the river outflows. For calculating the hydrological budget, the domain was subdivided in 17 watersheds, showed in Fig. 1.

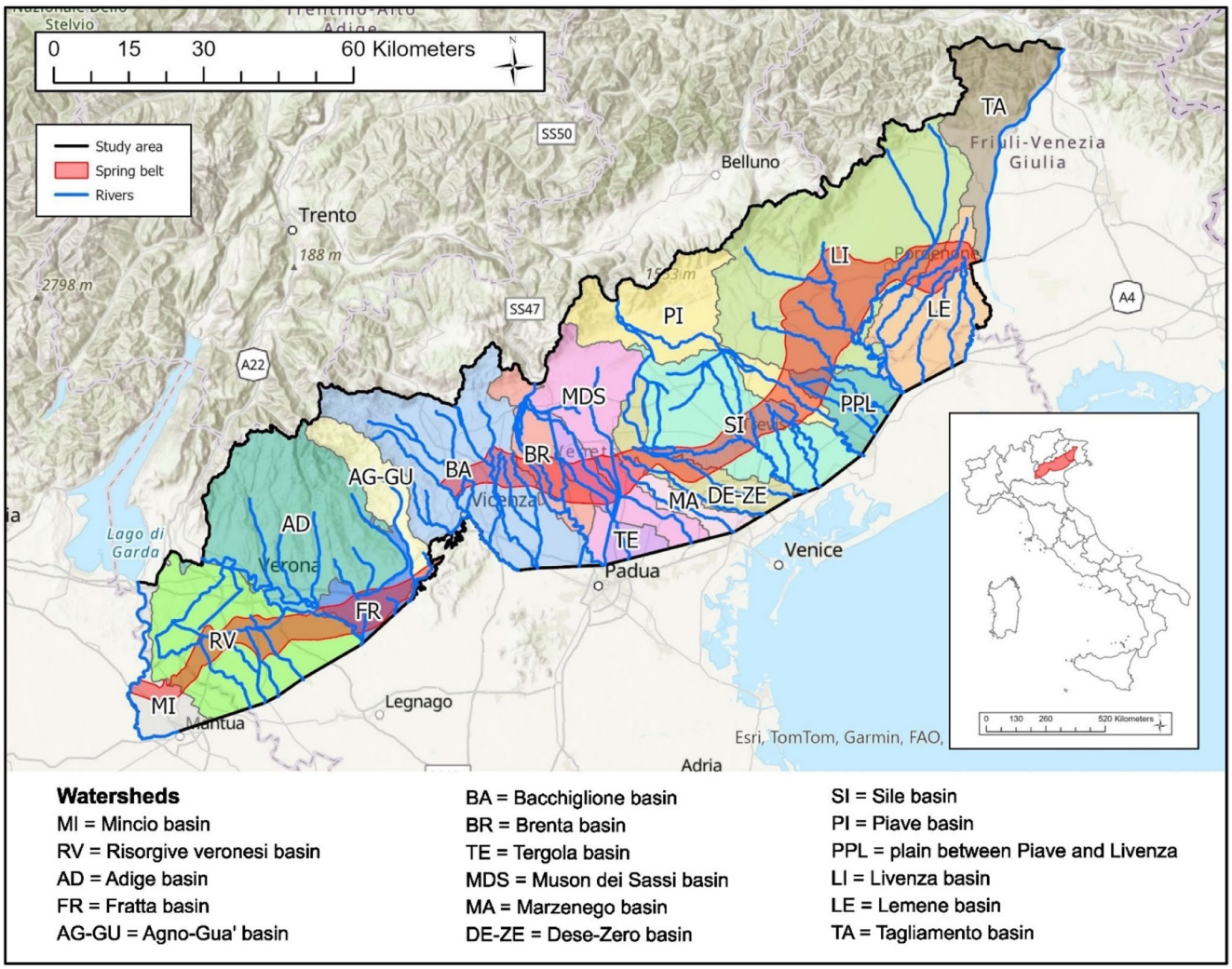


Fig. 1 Study area and delineated watersheds

Geological and hydrogeological settings

The Veneto-Friuli plain is an alluvial plain originating from the deposition of fluvioglacial and fluvial sediments, which constitute megafans. (Mozzi 2015; Fontana et al. 2014). In a megafan the grain size of the materials decreases from the area of settlement to distal zones, which in this case are respectively represented by the Alps and the Adriatic Sea, resulting in the transition from coarse-grained sediments to fine-grained sediments. Based on this type of sedimentation, the Venetian plain can be divided into three macro areas: the high plain, the middle plain and the low plain.

The high plain is proximal to the northern mountain reliefs (locally called Pre-Alps) and has a variable width. It is mainly composed of coarse materials, such as gravels and sands, which define a thick undifferentiated aquifer. The middle plain represents the transition zone between the high and low plains and is characterized by the spring belt, an area where natural groundwater emergence occurs, giving rise to rivers and characteristic plain springs called "fontanili"; this phenomenon is due to the intersection between the water table and the topographic surface (Fabbri and Piccinini 2013; Vorlicek et al. 2004). In the middle plain, the undifferentiated aquifer hosted in the high plain turns into a gravelly artesian multi-aquifer system. Further south, the low plain is characterized by fine materials such as silts and clays, interbedded with sandy levels. Consequently, the gravelly artesian multi-aquifer system of the middle plain evolves into a sandy confined multi-aquifer system in the low plain, extending to the Adriatic Sea.

From a hydrogeological point of view, the undifferentiated aquifer in the high plain represents the recharge area of the middle and low plain multi-aquifer system, since these aquifer systems are directly connected. The recharge is mainly provided by precipitation, river dispersion, irrigation practices, and groundwater inflows from rocky mountain aquifers. The transition from the undifferentiated aquifer to

the multi-aquifer system can be observed in Fig. 2, marked by the appearance of clay layers in the middle plain.

Materials and methods

An analytical hydrological budget was developed to quantify water uses over a period of 13 years, from 2010 to 2022. The fundamental hydrological budget equation states:

$$\sum IN = \sum OUT \pm \triangle S \quad (1)$$

and represents the mass conservation principle applied to a watershed, where:

- IN = inflows;
- OUT = outflows;
- ΔS = change of water storage.

Under natural long-term conditions, inflows and outflows are expected to be in balance, resulting in negligible changes in water storage. This equilibrium, however, may be altered by human activities or climate change. Among the objectives of this study is the quantification of such variations.

Equation (1) was rewritten expressing its parameters as follows:

$$P + Q_{in} + IF_{in} + GW_{in} + IW_{in} = AET + Q_{out} + IF_{out} + GW_{out} + EW_{out} \pm \triangle S \quad (2)$$

where the left side of the equation represents the inflows, while the right side represents the outflows and the water storage. In detail, the parameters of this equation are defined as:

- P = precipitation;
- Q_{in} = surface inflow in the domain of rivers and springs;
- IF_{in} = interflow inflow;
- GW_{in} = groundwater inflow in the domain from mountain rocky aquifers;
- IW_{in} = imported water, specifically anthropic inflow from water derivations coming from outside the study domain;
- AET = actual evapotranspiration;
- Q_{out} = surface outflow from the domain by rivers;
- IF_{out} = interflow outflow;
- GW_{out} = groundwater outflow from the domain;
- EW_{out} = exported water, specifically anthropic outflow, from water derivations and groundwater extraction transferred outside the domain.

In the present study, all terms of Eq. (2) were estimated directly or indirectly, except for the interflow. The interflow is the quantity of circulating water in the vadose zone, and since the dimensions of the study domain, both spatial and temporal, it was considered negligible in the water budget.

To investigate the change in water storage, trend analysis of precipitation and potentiometric level in groundwater were conducted for the period 2010–2022.

Hydrological budget inflows assessment

Precipitation (P)

For the estimation of precipitation, 219 meteorological stations of the regional agencies for environmental prevention and protection (ARPA) of Veneto, Friuli-Venezia Giulia and Lombardia, equipped with rain gauge, have been considered (Fig. 3). Each station measures precipitation height (mm) with a daily frequency. The daily measures were subsequently aggregated to obtain the monthly average value in the period 2010–2022, in order to mitigate the effect of the interannual variability of this parameter. Spatial interpolation has been performed to extend the information over the entire domain,

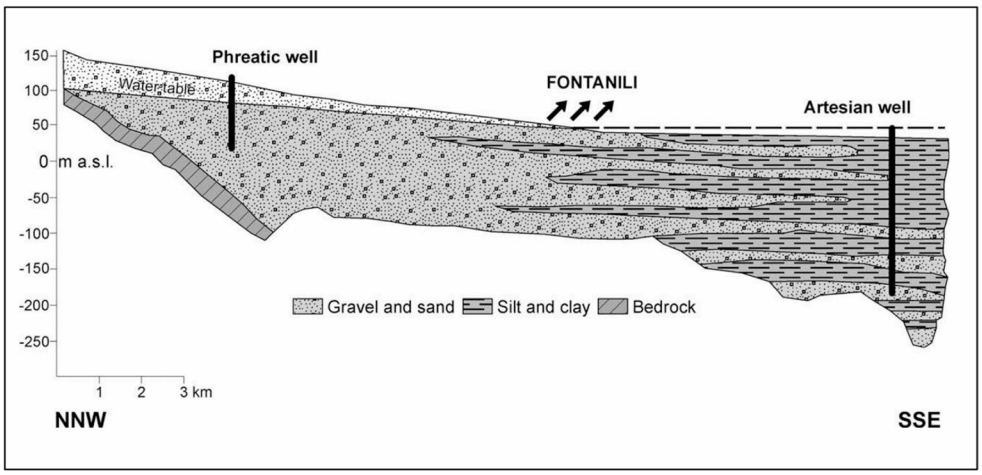


Fig. 2 Ideal cross section of the Veneto-Friuli plain (Piccinini et al. 2016)

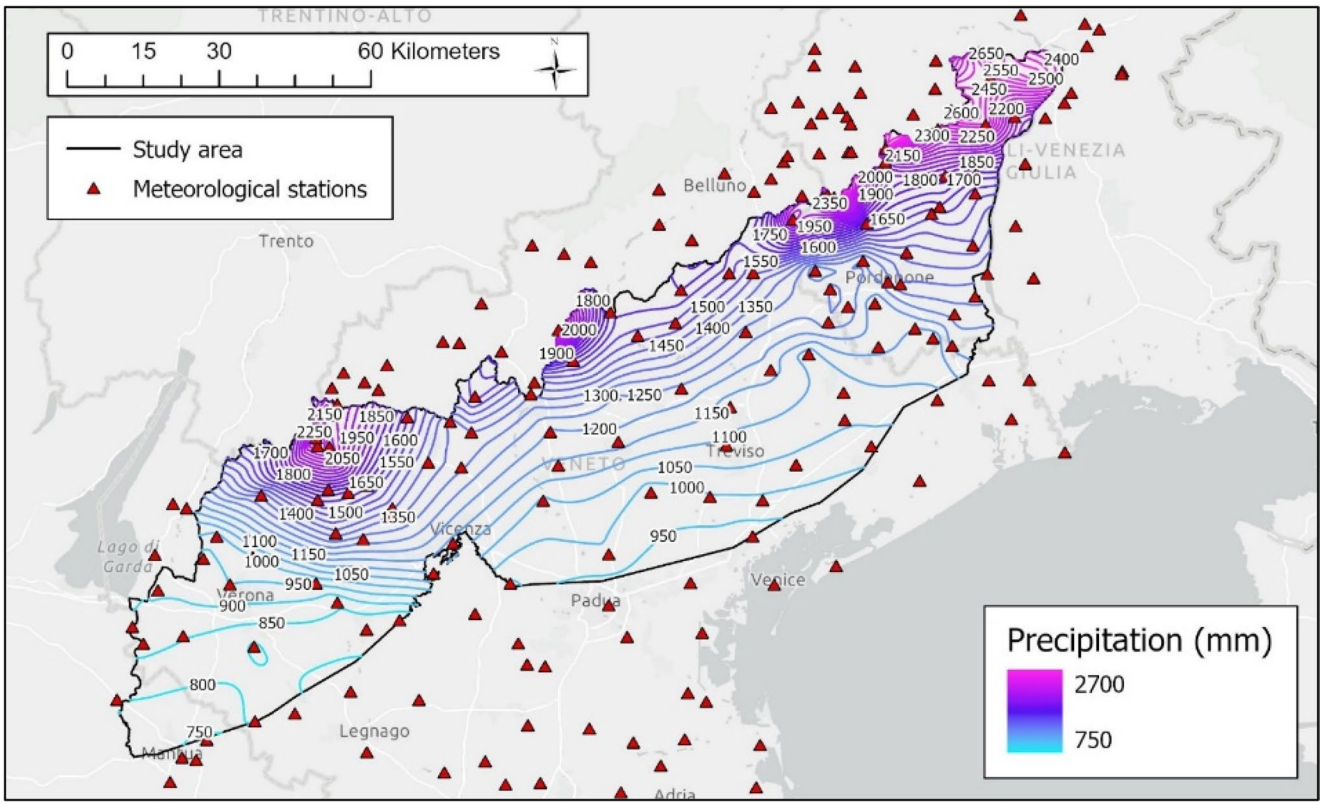


Fig. 3 Spatial distribution of precipitation in the domain, along with the meteorological stations used for the interpolation

using the natural neighbor algorithm (Sibson 1981) on square grid cells of 100 m. After this procedure, 12 maps of the average precipitation have been obtained, one for each month.

The average annual precipitation over the period 2010–2022 was obtained using ArcGIS Pro tools (ESRI 2023) that perform raster operations. In Fig. 3 the isohyets related to the average year are reported. The total precipitation for the period 2010–2022 resulted equal to 11079.4 M m^3/year.

Surface inflow (Q_{in})

Surface inflow refers to water from rivers and springs entering from outside the study area. If available, discharge values were obtained from discharge gauges, otherwise they were calculated from discharge rating curves or as average value from ARPA Veneto field measurements. Surface inflows were evaluated for each watershed within the domain; the results of this analysis are presented in Table 1, while their spatial distribution is shown in Fig. 4. The total amount of surface inflow was estimated at 12008.8 M m^3/year.

Groundwater inflow from mountain rocky aquifers (GW_{in})

Groundwater inflow represents the water flow occurring through preferential flow paths within the rock mass, which recharge the alluvial aquifers of the plain. This inflow occurs along the northern boundary of the domain, specifically at the ridges of the mountain reliefs (Pre-Alps). In literature, quantitative values for groundwater inflow across such a large area or even for its specific part are unavailable, as this parameter is difficult to measure directly and

Table 1 Hydrological budget components estimated for each watershed of the domain (in M m^3/year). Q_{in} = Surface inflow, IW_{in} = Imported water, Q_{out} = Surface outflow, QC_{out} = Anthropic surface water outflow

Watershed	Q_{in}	IW_{in}	Q_{out}	QC_{out}
Mincio	1803.1	-	430.6	1233.7
Risorgive Veronesi	-	-	532.8	-
Adige	2937	4303	6608.2	451.3
Togna-Fratta	-	-	63.4	55.8
Agno-Gua'	10.9	-	174.3	9.3
Astico-Bacchiglione	252.2	-	1034.7	39.7
Brenta	2157.8	122.7	1441.4	283.4
Muson dei Sassi	-	-	166.8	42.3
Tergola	-	-	60.1	38.2
Marzenego	-	-	37.5	13.3
Dese-Zero	-	-	206.6	-
Sile	-	6.3	1651.1	334
Piave	1651.5	1356	1659.2	6.3
Pianura tra Piave e Livenza	-	-	287.1	483
Livenza	704.8	2075	3097.7	-
Lemene	-	-	1070.4	69.4
Tagliamento	2491.3	947.5	546.6	753.7

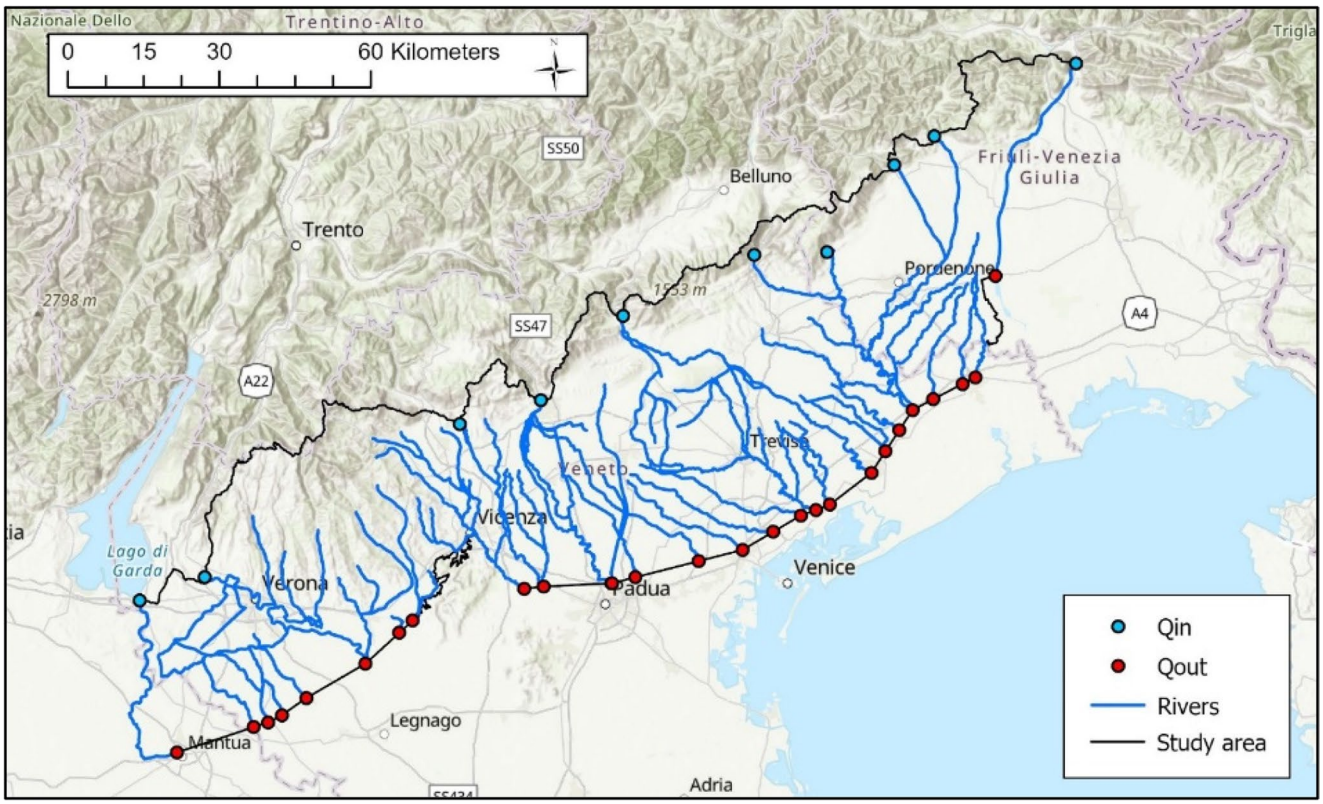


Fig. 4 Surface flow entry points (Q_{in}) and exit points (Q_{out}) along the domain boundaries

remains challenging to estimate. Although some tracer tests have been conducted in the area, their results are primarily qualitative rather than quantitative. These studies focus on the characterization of groundwater reservoirs (Kilchmann et al. 2004), karst aquifers (Vincenzi et al. 2011; Filippini et al. 2018; Spreafico et al. 2023; Zannoni et al. 2025), or the streamflow components of small watersheds (Zuecco et al. 2021). Considering this problem, as done by Fabbri et al. (2016), the groundwater inflow was estimated indirectly through the analysis of the hydrological budget results. The specific estimation procedures of the groundwater inflow are explained in the results and discussions section.

Imported water (IW_{in})

Imported water is the quantity of water entering in the domain by anthropic channels or pipelines coming from outside the study area. This water is usually employed for hydroelectric systems and/or for agricultural uses. The estimation of this parameter was carried out collecting data from unpublished reports by the main corps of hydroelectric production, land reclamation consortia and water management authorities. Most of these data refer to average concession rates and were considered in the hydrological budget, although the actual flow rates may be different depending on anthropic demand. The total anthropic inflow was estimated at 8810.5 M m^3/year, and the values referred to each considered watershed are listed in Table 1.

Hydrological budget outflows assessment

Actual evapotranspiration (AET)

The actual evapotranspiration represents the effective amount of water that evapotranspires in a certain area and depends on the amount of available water (Allen et al. 1998; Fisher et al. 2011). Within the study area, the primary components of evapotranspiration include fluxes derived from rainfall precipitation, irrigation and surface water bodies. For the purposes of this study, actual evapotranspiration was considered equal to potential evapotranspiration as a simplification, based on the general availability of water resources in the study area (Fisher et al. 2011). This assumption is justified since, during periods of rainfall scarcity, irrigation compensates the water supply and surface water bodies are present throughout the year, providing an additional and persistent source of water. Potential evapotranspiration represents the theoretical maximum evapotranspiration of a certain area. The following formula (3) shows the summarized simplification adopted in this study

$$PET \cong AET \cong AET_{rp} + AET_{ir} + AET_{sw} \quad (3)$$

Where:

- PET = potential evapotranspiration;
- AET = actual evapotranspiration;
- AET_{rp} = rainfall evapotranspiration;
- AET_{ir} = irrigation-depending evapotranspiration;
- AET_{sw} = evapotranspiration from surface water bodies.

The potential evapotranspiration was calculated using the Penman-Monteith equation proposed by FAO (4), one of the most widely adopted methods for large-scale evapotranspiration assessment (Allen et al. 1998; Fisher et al. 2011; Xue et al. 2025):

$$\mathrm{ET}_0 = \frac{0.408\triangle\left(R_n - G\right) + \Upsilon\frac{900}{\mathrm{T}+273}\mathrm{u}_2\left(\mathrm{e}_s - \mathrm{e}_a\right)}{\triangle + \Upsilon\left(1 + 0.34\,\mathrm{u}_2\right)} \quad (4) \qquad (4)$$

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 soil (m/s);
- e_s = saturated vapor pression (kPa);
- e_a = effective vapor pression (kPa);
- Δ = ratio of saturated vapor pression vs. temperature (kPa/°C);
- γ = psychrometric constant (kPa/°C).

The PET was calculated as ET_0, assuming the entire surface of the domain covered by a forage monoculture under well-watered conditions, the reference crop, as described in Allen et al. (1998). The reference crop is a short grass similar to alfalfa with 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 (Smith et al. 1992). The calculation of ET_0 was carried out in GIS environment, on square cells grid of 100 m, using average month values for the period 2010–2022. In this way, 12 potential evapotranspiration maps, one for each month, were obtained. The climatic data used in the analysis were temperature, solar radiation and wind velocity, coming from 220 meteorological stations of the Veneto, Friuli Venezia Giulia, and Lombardia regional ARPA agencies; these data were subsequently spatialized using natural neighbor interpolation algorithm. Some of the parameters included in the Penman-Monteith formula are generally not measured but can be calculated through empirical relations, provided in the FAO guidelines, starting from commonly measured meteorological parameters (Allen et al. 1998).

Using the same procedure adopted to calculate the average annual precipitation, the potential evapotranspiration for an average year in the period 2010–2022 was estimated at 7707.3 M m^3/year. Since it was assumed that $PET \cong AET$, an estimation of the AET and its components (AET_{rp}, AET_{ir}, AET_{sw}) was realized in order to verify if this simplification was acceptable and its validity.

Rainfall is one of the main water inputs within the domain; therefore, it was assumed that the majority of the evapotranspired volumes originates from this component. AET_{rp} was estimated by comparing the ET_0 raster with the P raster, applying the following conditions to each cell:

- if $ET_0 \geq P$, the actual rainfall evapotranspiration is equal to precipitation;
- if $ET_0 < P$, the actual rainfall evapotranspiration is equal to the potential evapotranspiration.

In this way, 12 maps of the average AET_{rp} were obtained. The annual average value for the period 2010–2022 was estimated by summing the raster values of each monthly map, resulting in the map shown in Fig. 5 and an AET_{rp} value of 6376.3 M m^3/year.

The actual evapotranspiration depending on irrigation (AET_{ir}) was calculated differently. Starting from the volumes of water used for crop irrigation, the amount of water which evapotranspires was estimated based on the irrigation methods, which were divided into two main categories: surface methods and pressure methods. Surface methods refer to traditional flood irrigation practices, while pressure methods aim to reduce water overconsumption, and include techniques such as sprinkler irrigation and micro-irrigation. Pressure methods reduce overall water consumption but also minimize infiltration: it is estimated that, with pressure systems, up to 90% of the delivered water is lost through evapotranspiration, compared to approximately 40% for surface methods (Dal Prà et al. 1998; Fabbri et al. 2016). The remaining water may infiltrate or generate surface runoff, with the proportions depending on soil type.

Irrigation in the study area is predominantly carried out by land reclamation consortia (LRCs) or by self-supply of private individuals, frequently practiced where LRCs do not reach the users. Land reclamation consortia are entities that manage public work of reclamation and oversee the activities of private users. Depending on the water distribution network, the irrigation areas can be classified as structured or unstructured. Structured areas are characterized by stable structures necessary for agricultural production and are typical of the high and middle plain, where coarse soils present low water retention capacity. In contrast, unstructured areas are typical of low plain, where the predominantly fine soils have a

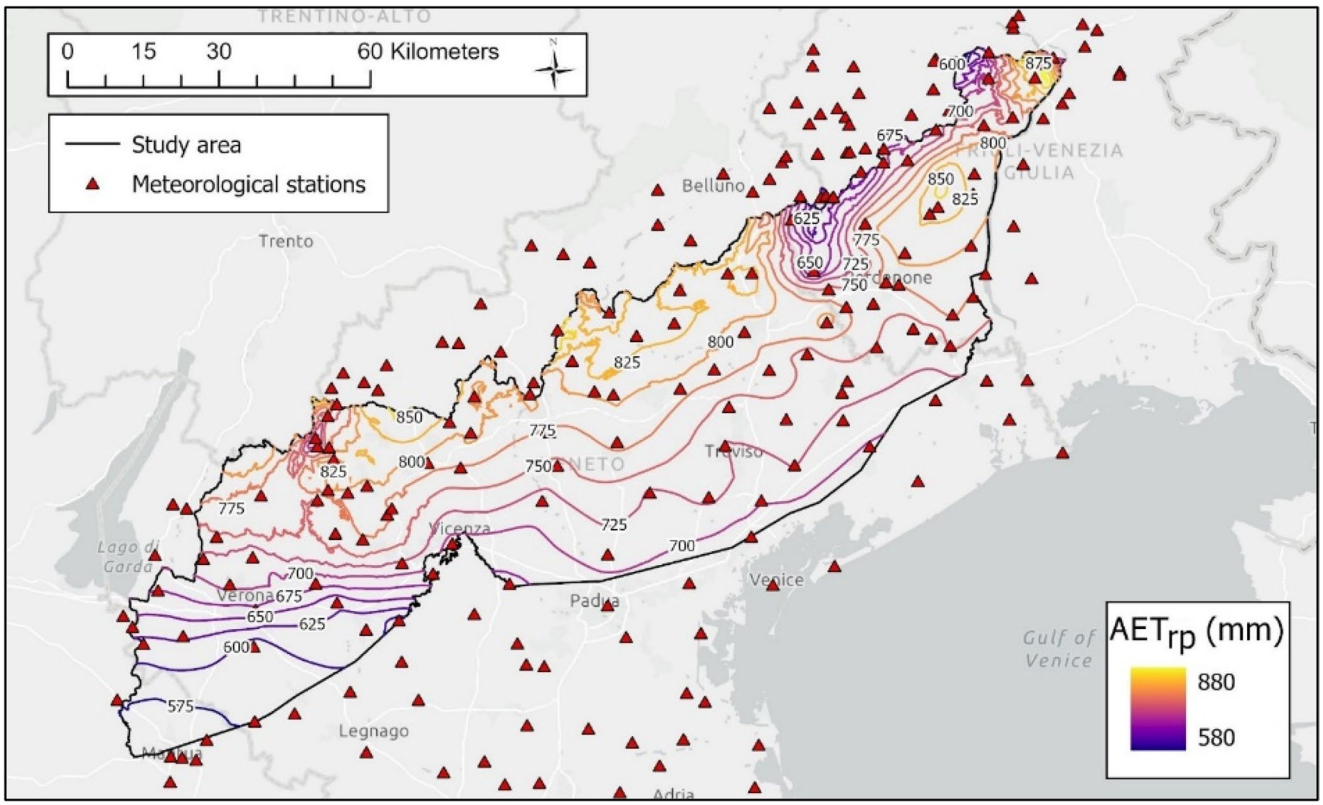


Fig. 5 Spatial distribution of the actual rainfall evapotranspiration in the domain, along with the meteorological stations used for the interpolation

good water retention capacity, and are characterized by emergency irrigation, ensuring an acceptable level of soil moisture through sporadic irrigation, according to the periods of greatest need. Structured and unstructured areas are characterized by different irrigation methods, with generally greater use of surface methods in structured areas than in unstructured ones, in which pressure methods predominate. Nevertheless, in recent years efforts have been made to increase the use of pressure methods even in structured areas.

For each irrigation district, the mean annual water volume was provided by the Eastern Alps Water Authority, and the percentages of each irrigation method were estimated based on the type of distribution network. It was estimated that, in the Veneto Region, the structured area is characterized by 41% pressure methods and 59% surface methods, while the unstructured area is characterized by 87.5% pressure methods and 12.5% surface methods. The portion of the Friuli-Venezia Giulia Region included in the domain for 90% of the area is irrigated using pressure systems and the remaining 10% with surface irrigation systems. In the Lombardia area no information were available about the irrigation methods, but, since it's recognized as an unstructured area, the same percentages for the unstructured Veneto area were used. The average annual volume delivered by LRCs was estimated at 1318.7 M m^3/year, while the volume of evapotranspired water was estimated at 633.1 M m^3/year.

The volumes used for self-supply irrigation in the Veneto Region were estimated by the Eastern Alps Water Authority based on consumption data from users not reached by the LRCs' irrigation network. For Friuli-Venezia Giulia, these volumes were obtained from the regional hydrogeological budget (Zini et al. 2011). In the case of the Lombardia Region, the water volumes were estimated by applying the same ratio of water volume to irrigated area as in the Veneto Region. Self-supply irrigation systems were assumed to use pressure methods, as these are the most commonly adopted by private users. Consequently, it was considered that 90% of the water volume undergoes evapotranspiration, while the remaining 10% infiltrates.

The average annual volume used for self-supply irrigation was estimated at 401.6 M m^3/year, while the amount of evapotranspired water was estimated at 361.5 M m^3/year. In total, therefore, the value of AET_{ir} was found to be 994.6 M m^3/year, by summing the irrigation values related to LRCs and those related to self-supply.

Knowing the values of PET, AET_{rp} and AET_{ir}, it was assumed that the remaining portion of evapotranspiration was related to surface water bodies, determining AET_{sw} from Eq. 3 and obtaining a value of 336.3 M m^3/year.

Surface outflow (Q_{out})

Surface outflow refers to the fluvial discharge leaving the domain through its southern boundary, and includes both the natural river flow and water pumped from wells and discharged into the drainage network. To evaluate surface outflow, discharge values were obtained from hydrometric monitoring stations, either directly through existing rating curves or by reconstructing them using ARPA field measurements. In river reaches where no measure was available, river outflows were determined using lithology dependent dispersion/drainage coefficients per linear kilometer. These coefficients, estimated in rivers with available discharge data, were calculated as ratio between the discharge values difference of two proximal monitoring stations and their linear distance. Once calculated they were subsequently applied to reaches with similar lithological characteristics. The total average annual surface outflow from the domain was estimated at 19068.4 M m^3/year, of which 17848.3 M m^3/year correspond to natural river flow and 1220.1 M m^3/year to anthropogenic drainage from private wells. The estimation of private pumping was conducted by the Eastern Alps Water Authority using data from the Italian National Statistics Institute (ISTAT), referring to household consumption by users not served by integrated water services. For Friuli-Venezia Giulia, the estimate was obtained from the regional hydrological budget (Zini et al. 2011), whereas no data were available for the Lombardia Region. Table 1 reports the average annual surface outflows for each watershed within the domain, and the main outflow points are illustrated in Fig. 4.

Groundwater outflow (GW_{out})

Groundwater outflow refers to the groundwater leaving the domain through aquifers located along the southern boundary of the study area. This contribution was estimated based on a previous detailed study conducted within the Venice Lagoon Basin Council area (Fabbri et al. 2016), which identified a groundwater outflow coefficient of 22.1 M m^3/year/km. Considering the more southern location of the boundary in this study, characterized by less permeable materials compared to the previous analysis, the coefficient was adjusted to 5.525 M m^3/year/km, based on the hydrogeological properties of the new boundary zone. This value reflects a multi-aquifer system with an overall aquifer thickness of approximately 100 m, an effective porosity of 15%, a hydraulic gradient of 0.12%, a hydraulic conductivity of about 10^{-3} m/s, and an average groundwater flow velocity of 1 m/day. By applying the adjusted coefficient to the 181 km length of the southern boundary, the estimated total groundwater outflow resulted 1000.0 M m^3/year.

Exported water (EW_{out})

The exported water is the quantity of water leaving the domain through anthropogenic channels or pipelines. It includes both surface water and groundwater withdrawals, managed by private or public authorities.

The anthropic surface water outflow (QC_{out}) is related to a complex network of channels and pipelines generally used for irrigation, production of hydroelectric energy, and surface water drainage. Most of these data, as the imported water (IW_{in}), are referred as average concession rates. Anthropic surface water outflow was evaluated in each of the watersheds analyzing their hydraulic schemes, and the average annual value was estimated equal to 3813.4 M m^3/year. The results are listed in Table 1.

Groundwater transferred outside the domain (GWE_{out}) is intended for human consumption and managed by water management agencies. It was assumed that all the withdrawn volumes are entirely consumed and do not return to the study area. For the Veneto Region, a value of 499.3 M m^3/year was obtained from data provided by the Eastern Alps Water Authority. For Friuli-Venezia Giulia, groundwater withdrawal was obtained from the regional hydrogeological budget (Zini et al. 2011), amounting to 42.7 M m^3/year. No data were available for the Lombardia portion of the domain; however, given its limited extent, groundwater withdrawal from this area was considered negligible. The total amount of groundwater transferred outside the domain was thus estimated at 542.0 M m^3/year. Considering both surface outflow and groundwater withdrawal, the total exported water was estimated at 4355.4 M m^3/year.

Trend analysis

For the trend analysis, data from 185 meteorological stations equipped with precipitation gauges and 100 wells or piezometers were analyzed. The groundwater level measurement points belong to the phreatimetric monitoring network, and therefore the recorded values are representative exclusively of phreatic aquifers. Considering that precipitation is one of the most important factors in groundwater recharge, precipitation trends were initially analyzed to investigate whether potential changes in groundwater levels could be explained by variations in precipitation patterns. If a direct relationship between the two trends were observed, variations in potentiometric levels could be attributed to changes in precipitation, potentially influenced by climate change. Conversely, if no such relationship were found, the observed decline in groundwater potentiometric levels could be explained by increased groundwater exploitation.

The trend analysis was conducted at monthly, four-monthly, annual and seasonal scales in R environment (R

Core Team 2025) using the package "modifiedmk" (Patakamuri and O'Brien 2021), a modification of the Mann-Kendall test that evaluates the trends in presence of autocorrelated data (Hamed and Rao 1998). The missing data of the time series, both for precipitation and potentiometric levels, were estimated using machine learning techniques with the package "miceRanger" (Multiple Imputation by Chained Equations with Random Forests; Wilson 2021). To assess the variations in precipitation and groundwater levels between the years of the period 2010–2022, annual trends were considered (Fig. 6).

Regarding precipitation measurements, a negative trend was observed only at the seasonal scale, specifically in autumn, while no significant trends emerged at the monthly, four-monthly, or annual scales. This indicates a shift in the temporal distribution of precipitation, although the total annual amounts remain relatively constant throughout a hydrological year. In contrast, the trend analysis of groundwater levels revealed negative trends across all time scales. The results of the trend analysis for the monitoring stations exhibiting a trend are presented in Tables 2 and 3, for precipitation and groundwater levels respectively. Despite the absence of significant precipitation trends during that period, as shown in Fig. 6a; Table 2, a negative annual trend was identified at 16 groundwater monitoring points (Fig. 6b; Table 3).

Results and discussions

The estimation of the quantifiable terms in the water budget Eq. (2) allowed for the calculation of total inflows ($\sum_{IN}$), equal to 31898.7 M m^3/year, and total outflows ($\sum_{OUT}$), equal to 32131.1 M m^3/year.

Among the inflows, precipitation amounted to 11079.4 M m^3/year, surface inflow to 12008.8 M m^3/year, and anthropic inflow to 8810.5 M m^3/year, while groundwater inflow has not yet been evaluated. The estimation is considered

Table 2 Results of the analysis on the annual time series for rainfall monitoring stations showing a trend

ID	Original *p*-value	Corrected *p*-value	τ	Sen's slope (mm/year)
P1	0.024	0.024	−0.48	−36.26
P2	0.160	0.037	−0.30	−54.30
P3	0.076	0.006	−0.38	−49.54
P4	0.076	0.016	−0.38	−67.68

Table 3 Results of the analysis on the annual time series for potentiometric level monitoring stations showing a trend

ID	Original *p*-value	Corrected *p*-value	τ	Sen's slope (m/year)
L1	0.003	0.003	−0.77	−0.14
L2	0.002	0.080	−0.80	−0.46
L3	0.024	0.024	−0.49	−0.03
L4	0.017	0.017	−0.51	−0.05
L5	0.006	0.006	−0.59	−0.12
L6	0.044	0.006	−0.44	−0.09
L7	0.024	0.024	−0.49	−0.05
L8	0.006	0.006	−0.59	−0.17
L9	0.044	0.044	−0.79	−0.46
L10	0.044	0.044	−0.44	−0.17
L11	0.044	0.044	−0.44	−0.15
L12	0.024	0.024	−0.49	−0.12
L13	0.009	0.009	−0.56	−0.17
L14	0.024	0.000	−0.54	−0.14
L15	0.009	0.009	−0.56	−0.21
L16	0.024	0.024	−0.49	−0.12

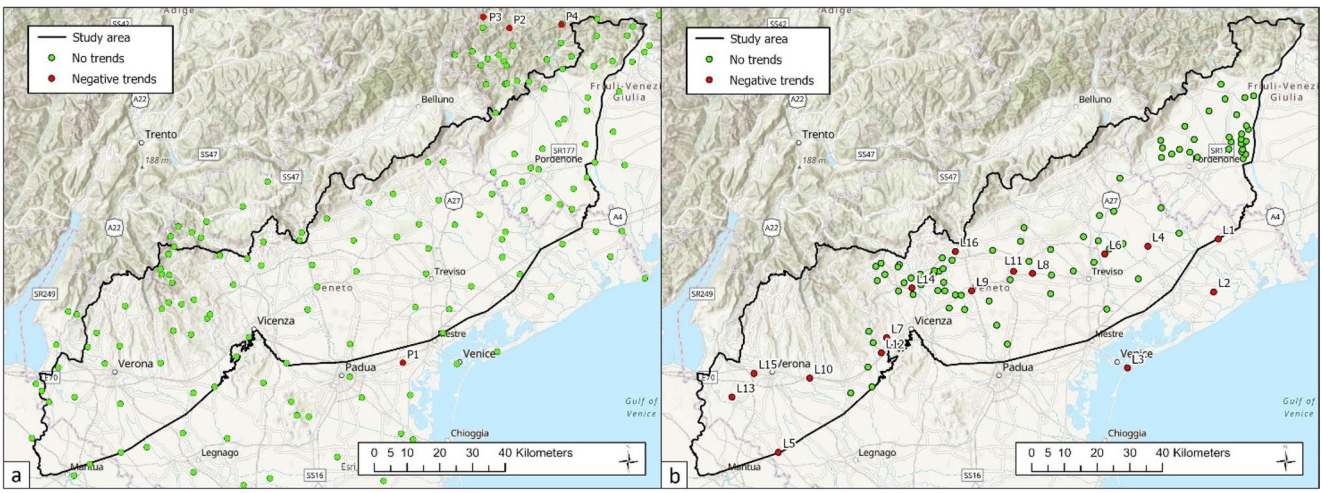


Fig. 6 Measurement stations used for trend analysis of precipitation (a) and potentiometric levels (b), showing the IDs of stations with negative trends reported in Tables 2 and 3

reliable for both precipitation and surface inflow, as these values largely derive from the processing of data collected at monitoring stations. In contrast, anthropic inflows could be affected by an overestimation, since they are based on the concession flow rates.

Regarding the outflows, actual evapotranspiration amounted to 7707.3 M m^3/year, surface outflow to 19068.4 M m^3/year, anthropic outflow to 4355.4 M m^3/year, and groundwater outflow to 1000.0 M m^3/year. The estimation is considered realistic for evapotranspiration, as it is largely based on data from monitoring stations and spatial analysis; however, it should be noted that the result is dependent on the chosen calculation method (Fisher et al. 2011; Xue et al. 2025). For surface outflow, it is believed that the majority of water volumes are represented, although only the main watercourses were considered in the calculation. Anthropic outflows, like anthropic inflows, were derived from concession flow rates and, therefore, are subject to variations depending on human uses. To evaluate the discrepancies between the concession and the actual rates, data from six monitoring stations in strategic structures, primarily located on the Piave and Adige watersheds, were collected by the Eastern Alps Water Authority for the period 2022–2025. Their comparison, defined as percent discrepancy between actual water uses and concession rates, indicates that actual water uses are lower than the concession rates. In detail, the maximum observed reductions were 40% (164.62 M m^3/year) and 26% (160.20 M m^3/year) for anthropic inflows and anthropic outflows, respectively. Since the monitoring period differs from that used for the water budget, and the data are available only starting from 2022, a year characterized by severe drought, these results may be influenced by significant deviations from long-term average conditions; nonetheless, they provide a useful indication of the overestimation associated with concession data. Groundwater outflows, although realistic, may be subjected to significant uncertainty due to the use of indirect estimation methods. Overall, the values estimated for the main terms of the water budget are considered to be representative of the regional-scale hydrological cycle, particularly in terms of their order of magnitude. The results of this analysis are shown in Fig. 7.

On the basis of the estimated inflows and outflows, a negative imbalance of 232.4 M m^3/year was observed. A hypothesis 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 rock aquifers (GW_{in}) and storage variation (ΔS).

These parameters, which are associated with groundwater resources, were evaluated through trend analysis. Despite the absence of significant precipitation trends

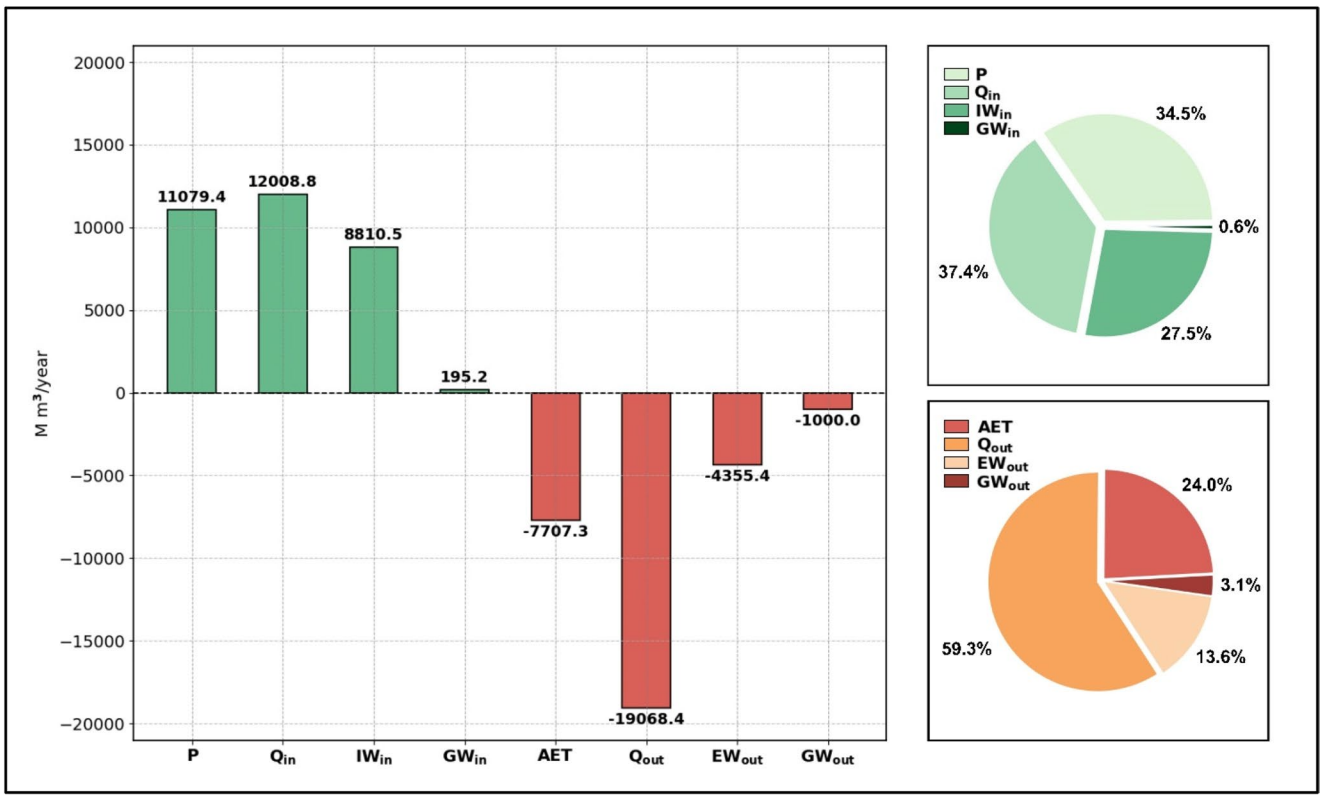


Fig. 7 Principal components of the hydrological budget

during the period 2010–2022, a negative annual trend in potentiometric levels was identified at 16 groundwater monitoring points. The 100 groundwater level measurement points, spatially distributed across the Venetian plain, were considered representative of the groundwater resource. Based on this assumption, 16% of the calculated negative imbalance was attributed to ΔS, while the remaining 84% of the imbalance was indirectly attributed to GW_{in}. As a result, the calculated imbalance of 232.4 M m^3/year was subdivided, with 37.2 M m^3/year attributed to ΔS and 195.2 M m^3/year to GW_{in}. In addition, the discrepancy between annual trends of precipitation and potentiometric levels suggests that the observed decline in groundwater levels may be primarily attributed to anthropogenic factors, such as increased groundwater abstraction, rather than to climate change impacts during the water budget period.

To evaluate the results of the developed analytical water budget, they were compared with those of other studies covering the same area and period. From the national-scale hydrological model BIGBANG 8.0, developed by ISPRA (Braca et al. 2023), it was possible to compare precipitation and actual evapotranspiration, while with the MODIS project (Moderate-resolution Imaging Spectroradiometer; Running et al. 2019) the terrestrial ecosystem and potential evapotranspiration. BIGBANG is a GIS-based model designed to compute the components of the hydrological budget at the national scale, using regular square cells of 1 km, based on the EEA Reference Grid for Italy. The model provides data at monthly resolution starting from 1951. MODIS is part of NASA/EOS project developed to estimate evapotranspiration (terrestrial ecosystem and potential) and heat flux (latent and potential latent) of the earth land surface by using satellite remote sensing data with 500 m spatial resolution and an 8-day, monthly and annual temporal resolution. Its dataset covers the years starting from 2000.

Referring to the precipitations, the value estimated by the BIGBANG model amounted to 11297 M m^3/year, showing good agreement with the corresponding value of 11079.4 M m^3/year obtained in the present study. The main discrepancies are related to evapotranspiration estimates. While the BIGBANG model and the MODIS project estimated 5007 M m^3/year and 4831.2 M m^3/year, respectively, the value obtained in this study is 7707.3 M m^3/year, resulting in a difference of approximately 35%. Regarding the BIGBANG model, this divergence is primarily attributable to the different methods used to calculate potential evapotranspiration, since the BIGBANG model employs the temperature-based Thornthwaite and Mather method (1955), whereas this study adopted the FAO Penman-Monteith method (Allen et al. 1998). It is well established that such methodological differences can lead to discrepancies exceeding 25%, with temperature-based approaches typically underestimating evapotranspiration compared to methods that also incorporate solar radiation (Fisher et al. 2011). In the context of this regional-scale analysis, the FAO Penman-Monteith method is considered appropriate, as the resulting evapotranspiration estimate is consistent with the other components of the hydrological budget. For the MODIS project, as reported in Ruhoff et al. (2013), the lower value of evapotranspiration, although based on the Penman-Monteith method (MOD16 algorithm), can be primarily related to an underestimation due to the application of different land use/land cover classification. In contrast, in this study, constant average meteorological data were utilized, and it was assumed that the entire domain was covered by a reference crop (alfalfa) under well-watered conditions.

Adopting the lower BIGBANG or MODIS value would lead to a positive imbalance, which would be inconsistent with the observed decreasing trends in groundwater levels. Moreover, the FAO Penman-Monteith equation was also successfully applied in Gatto et al. (2023), where an Integrated Surface–Subsurface Hydrological Model (ISSHM) was developed for a portion of the territory included in the present study area. In that work, evapotranspiration was estimated as potential crop evapotranspiration (ET_c), derived from the reference evapotranspiration (ET_0) and crop coefficients (K_c), which vary depending on vegetation type and time of year. For the purposes of this regional-scale analysis, crop coefficients were not included in the calculation of potential evapotranspiration, assuming the entire domain to be uniformly covered by the reference crop.

A comparison was also conducted with the water budget developed by Fabbri et al. (2016), which pertains to an area located within the current study domain, covering approximately 9.8% of its total extent. When considering only the area corresponding to that of the 2016 study, the water volumes estimated in the present analysis are generally comparable to those reported by Fabbri et al. (Table 4), with the exception of actual evapotranspiration and exported water, which exhibit more significant

Table 4 Comparison between the inflow and outflow parameters of the hydrological budget estimated in this study and Fabbri et al. (2016), in M m^3/year

Budget term	This study	Fabbri et al. 2016
P	1011.6	867.2
Q_{in}	1703.9	1350
IW_{in}	1205.6	1120
AET	763.1	1400
Q_{out}	1956.8	2023
EW_{out}	175.6	91

differences. The discrepancy in AET arises from the different methodological approaches adopted in the two studies, which led to a lower value in the present study. Regarding EW_{out}, the data collection carried out for this study, along with updated estimates provided by the Eastern Alps Water Authority, has contributed to a more accurate assessment of groundwater abstractions from wells, particularly by increasing the estimated contribution of private withdrawals.

Conclusions

The assessment of water volumes involved in the hydrological cycle is a key objective for the effective management of water resources, which are at risk of becoming less available due to climate change and human overexploitation, even in traditionally water-rich countries. This study presents the first regional-scale water budget for the Veneto-Friuli Plain, in northeastern Italy, covering an area of approximately 8700 km^2 and referring to the period 2010–2022. Each component of the water budget Eq. (2) was quantified, enabling a comprehensive assessment of the hydrological dynamics of the domain. The following key findings emerged from the analysis:

- rainfall within the study area contributes less to the system inflows than surface water originating outside the domain, particularly from the Alpine mountain region;
- regulated flows related to hydroelectric production and irrigation are of comparable magnitude to natural river discharges;
- low-consumption irrigation practices tend to increase evapotranspiration, reducing infiltration and groundwater recharge;
- groundwater abstraction through private wells enhances surface outflows, leading to the depletion of groundwater resources;
- uncertainties in the water balance primarily concern the groundwater-related components, which were estimated using indirect methods, thereby highlighting the need to enhance the groundwater monitoring network or the realization of regional tracer tests.

These considerations are supported by the volumetric estimates obtained through the water budget. Specifically, among the inflows, 34.5% is attributed to precipitation, 37.4% to surface inflows, 27.5% to imported water, and only 0.6% to groundwater inflows. Regarding the outflows, 24.0% is attributed to evapotranspiration, 59.3% to surface outflows, 13.6% to exported water, and 3.1% to groundwater outflows. A negative change in water storage due to overexploitation was identified, as indicated by the Mann-Kendall trend analysis conducted on precipitation and groundwater level data. This change was quantified at approximately 37.2 M m^3/year, consistent with the modest declining trend in potentiometric levels observed between 2010 and 2022.

The analytical water balance proved to be an effective and practical tool for quantifying inflows and outflows over such a large region, where data availability is generally good but remains limited for certain components of the hydrological cycle. This approach allows for clear communication of results and supports informed decision-making. At the regional scale, analytical water budgets represent essential tools for water resource management, as they also allow for the identification of monitoring gaps and help guide improvements in data collection strategies.

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Author contributions R.T., D.C., L.P., and P.F. contributed to material preparation, data collection and data analysis. P.F. and L.P. were responsible for the conceptualization of the study, while R.T. and D.C. drafted the original manuscript. All authors participated in the review and editing of the final manuscript.

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Data availability The public data used in this study were obtained from the websites of the regional agencies for environmental protection and prevention (ARPA) of Veneto (ARPAV), Friuli-Venezia Giulia (ARPA FVG), and Lombardia (ARPA Lombardia). The remaining data are owned by the Eastern Alps Water Authority.

Declarations

Competing interests The authors declare no competing interests.

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