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REPORT

Comparing traditional and parametric groundwater budget methods to assess recharge in fractured karst aquifers: Insights from the Scirca spring (central Italy)

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Abstract

This study investigates the strategically significant Scirca spring, located at the foot of the Cucco Mountain karst massif in central Italy. The research aims to compare spring recharge estimates derived from traditional groundwater budget approaches with those obtained through the APLIS parametric method. Both methodologies were applied within a well-defined recharge area, delineated through comprehensive geo-structural and hydrogeological surveys, thereby ensuring a robust framework for analysis. Recharge estimates were calculated using the Thornthwaite–Mather water balance method, which is based on long-term precipitation and temperature data, and a modified APLIS method, which quantifies recharge as a proportion of precipitation based on topography, soil type, lithology, karst features, and the presence of structural lineaments. Results from the modified APLIS method aligned closely with those from the traditional groundwater budget approach, particularly under the assumption of minimal surface runoff within the recharge area. The cross-validation of both methods highlighted their reliability and complementarity in the context of karst environments. Notably, the modified APLIS method proved especially effective in capturing the influence of tectonic structures on recharge, underscoring its potential as a valuable tool for assessing groundwater recharge in fractured and tectonically active aquifers.

Keywords Aquifer recharge · Carbonate aquifer · Karst · Fractured media · Central Italy

Introduction

Carbonate fractured and karstified aquifers serve as vital water resources for millions of people worldwide (Bakalowicz 2015; Goldscheider et al. 2020; Hartmann et al. 2014; Stevanović, 2019; Xanke et al. 2024) and must be considered strategic to appropriately develop human society and maintain environmental quality (Davis et al. 2002).

Besides being usually characterized by high-quality water, high permeability, and significant storativity, these aquifers are frequently located, particularly in Europe, in mountain ridges, so to receive relevant precipitation rates, partly in the form of snow persisting on soil for several months per year (Fronzi et al. 2020; Lorenzi et al. 2022; Rusi and Di Giovanni 2025). Due to these characteristics, millions of people rely on these aquifers as their main source of water for their life and various activities (Parise et al. 2018; Stevanović, 2019).

Despite their significance, the complexity of such aquifers is due to peculiar groundwater dual-flow mechanisms (through karst conduits and fracture network) and thus poses challenges for accurately quantifying recharge rates. Moreover, the recharge/discharge equilibrium of such groundwater systems, affected by relevant human withdrawals since at least the former century, is now threatened by a risk of depletion due to climate change, which often alters

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recharge–discharge mechanisms and sometimes reduces the water availability (Havril et al. 2018; Fiorillo et al. 2021; Azimi et al. 2023; Filippini et al. 2024).

In this framework, to achieve sustainable management of karst–carbonate groundwater systems, it is vital to understand the processes governing their water budget (Gunn 2021; Iacurto et al. 2021).

To evaluate aquifer groundwater budgets, traditional approaches based on precipitation and temperature data can be used, at different temporal averaging scales, to estimate the amount of evapotranspiration, and its difference from precipitation, the resulting water surplus (Chen et al. 2018; Nimmo et al. 2005; Manghi et al. 2009; Fronzi et al. 2022, among others). A portion of the water surplus contributes to effective infiltration, which is primarily governed by the interaction between surface water and subsurface geological features (Rasmussen and Evans 1993; Salve et al. 2008). The rate and extent of this process depend largely on the permeability and structural characteristics of the subsurface materials, particularly the nature of the lithologies involved (Celico 1988; Viaroli et al. 2018). In regions dominated by well-developed karst systems, infiltration tends to be highly efficient, often allowing a significant fraction of precipitation to rapidly percolate underground (Liu et al. 2025). During periods of low evapotranspiration, infiltration can approach the magnitude of total precipitation, highlighting the key role of subsurface pathways in regulating groundwater recharge (Lorenzi et al. 2022).

Besides neglecting some peculiar characteristics of karst aquifers, such as rapid infiltration, and other factors beyond lithology influencing the infiltration rate, the main weak point of these methods depends on the scarce occurrence and/or poor quality of thermo-pluviometric data characterizing many mountainous areas where most karst aquifers are located (Allocca et al. 2014).

In recent decades, advances in the acquisition, storage, and analysis of diverse territorial data (i.e., geological, morphological, and soil properties) have facilitated the development of methods for estimating groundwater recharge by integrating surface characteristics such as geology, morphology, and soil properties. Among these, one of the most widely recognized approaches for karst aquifers is the APLIS method (Andreo et al. 2008), which estimates recharge as a percentage of rainfall based on factors including elevation, slope, lithology, infiltration landforms, and soil type. This method has been widely used in many settings, in its original version and by including different kinds of modifications as well (Espinoza et al. 2015; Entezari et al. 2020; Syafarini et al. 2021; Errahmouni et al. 2022).

For instance, Entezari et al. (2020) pointed out that the original APLIS model ignores the role of joints and fractures, despite their importance in the recharge of fractured karst aquifers. The authors proposed a modified APLIS method that accounts for the role of tectonic discontinuities in defining the preferential infiltration zones.

The choice of using a parametric method rather than a traditional approach to evaluate the recharge in karst aquifers is often forced by the scarce occurrence of reliable temperature and rainfall time-series data. It seems therefore useful when both territorial and climatic data are available for a given area to compare the results of both approaches to make a cross-check and evaluate whether they provide similar results (Mazza et al. 2014).

In this work, thanks to the availability of both territorial data and reliable time series for temperature, rainfall, snow depth, and spring discharge, the recharge amount to the Scirca spring, located in the Northern Apennines (Italy), was evaluated by using the traditional Thornthwaite–Mather water balance method and the multiparametric APLIS method. This spring is of crucial importance, as it has supplied drinkable water not only to the surrounding villages but also to Perugia, the chief town of the Umbria region, since the 1930s.

The recharge estimated by both methods was then compared to the annual recharge rate that was recently obtained by Fronzi et al. (2025), using the Turc method (Turc 1954). After a detailed reconstruction of the spring recharge area and the aquifer geometry, using the Visual KARSYS 3D model (Malard et al. 2019), the modified version of the APLIS method was applied, which considers both the presence of faults and their damage zones, and the presence of typical karst infiltration landforms. This approach allowed for the comparison of results to check the reliability of different methods and to assess how the obtained results can complement each other.

To summarize, this work aims to:

1) quantify recharge using both traditional (Thornthwaite–Mather) and parametric (modified APLIS) methods.
2) evaluate the advantages and limitations of both and assess their complementarity.
3) assess the implication for groundwater management in fractured and karst systems.

Materials and methods

Geological and hydrogeological setting

The Scirca spring is located on the western slope of the Cucco Mt. Massif, an anticline with eastward vergence, which is part of the Umbria–Marche Apennines Mountain Chain in central Italy. This chain is a fold-and-thrust belt formed in the Middle Miocene, later affected by SW–NE extensional tectonics, active since the early Pleistocene and responsible for the present seismicity of the area (Barchi and Mirabella 2009).

The outcropping rocks belong to the Mesozoic–Cenozoic Umbria–Marche multilayered sequence, with alternating limestone and marl formations. The oldest unit, widely outcropping in the anticline core, is the Upper Triassic–Lower Jurassic Calcare Massiccio (MAS), a limestone originated in a carbonate platform disarticulated into different domains during a Jurassic extensional tectonic stage. A well-developed karst system, characterized by caves exceeding 900-m depth with a total length > 20 km is found in this formation (Passeri 1971; Guzzetti 1987; Galdenzi and Menichetti 1995; Galdenzi 2009). The lowest elevation of the known karst system is slightly higher (about 45 m) above the elevation of the Scirca spring (575 m a.sl.).

Following the disarticulation and subsequent partial inundation of the carbonate platform of the Calcare Massiccio, testified by the presence of Mesozoic normal faults separating structural highs from basin areas, the deposition of two different Jurassic sequences occurred. A complete sequence, deposited in the deepest areas (grabens) and with an overall thickness of about 400 m, is composed of five Jurassic formations. The Corniola (COI) is a micritic limestone with chert, displaying regular stratification, while the remaining four formations (Marne del M. Serrone, Rosso Ammonitico, Calcari e Marne a Posidonia, and Calcari Diasprigni, RSN, RSA, POD, and CDU, respectively) have significant clayey–marly components. A reduced sequence, in which an about 100-m-thick single formation known as Bugarone (BU) overlays the Calcare Massiccio, was deposited in the shallowest sectors (horsts) (Fig. 1). The Bugarone Formation, despite being generally less marly than most of the formations of the complete sequence, has a marly component in this area.

In both successions, the Jurassic formations are overlain by Maiolica (MAI), an Early Cretaceous pelagic limestone, respectively 300 and 100 m thick in the complete and the reduced sequences. Above the Maiolica, the stratigraphy is more uniform in terms of thickness and is composed of the Marne a Fucoidi (FUC) and the Scaglia Group, which includes two calcareous formations (Scaglia Bianca, SBI, and Scaglia Rossa, SAS) and two marly

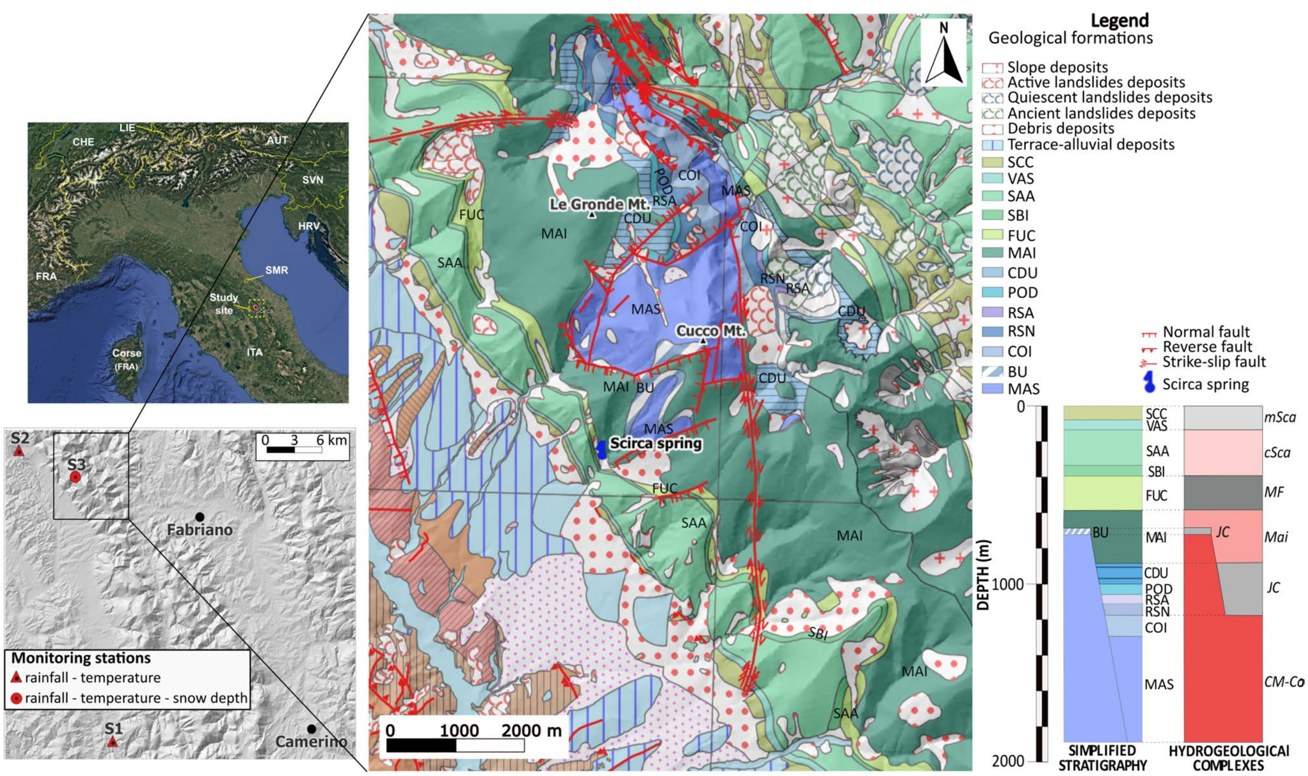

Fig. 1 Location of the study site and thermo-pluviometric sensors, and geological map of the Scirca spring area (modified after Regione Marche, 2002; Regione Umbria, 2015). *MAS* Calcare Massiccio (Hettangian–Sinemurian), *BU* Gruppo del Bugarone (Upper Toarcian–Lower Tithonian), *COI* Corniola (Sinemurian–Pliensbachian), *RSN* Marne del M. Serrone (Lower Toarcian), *RSA* Rosso Ammonitico (Middle–Upper Toarcian), *POD* Calcari e Marne a Posidonia (Aalenian–Bathonian), *CDU* Calcari Diasprigni (Bathonian–Kimmeridgian), *MAI* Maiolica (Tithonian–Lower Aptian), *FUC* Marne a Fucoidi (Lower Aptian–Lower Albian), *SBI* Scaglia Bianca (Upper Albian–Turonian), *SR* Scaglia Rossa (Upper Turonian–Middle Eocene), *VAS* Scaglia Variegata (Middle Eocene–Upper Eocene), *SCC* Scaglia Cinerea (Upper Eocene–Upper Oligocene)

formations (Scaglia Variegata, VAS, and Scaglia Cinerea, SCC) (Fig. 1).

In the study area, the calcareous formations serve as aquifers, while the marly formations primarily act as aquitards. The main aquifer is hosted in the Calcare Massiccio and, where present, in the Corniola Formation. These two formations form the CM–Co hydrogeological complex (Fig. 1), generally recognized as the Basal aquifer (Boni et al. 2010). The hydrogeological complex is often stratigraphically separated from the Maiolica (Mai in Fig. 1) by the low-permeability Jurassic complex (*JC* in Fig. 1), formed by the complete/reduced Jurassic sequences described above. Nonetheless, in the Scirca spring area, the Basal aquifer (CM–Co) is hydraulically connected to the Maiolica one (MAI) through normal faults. The Marne a Fucoidi Formation is a hydrogeological complex on its own (*MF* in Fig. 1) and represents the main aquitard of the whole sequence, above which lies the calcareous Scaglia complex (*cSca* in Fig. 1), the uppermost aquifer of the Umbria–Marche multilayer, overlayed by the low-permeability *mSca* marly complex. The Scirca spring emerges at the contact between the Maiolica and the Marne a Fucoidi formations. Other springs emerging on the western slope of Cucco Mountain, at the contact between Maiolica and Marne a Fucoidi (Acquasanta, 567 m a.s.l.; Gorghe, 518 m a.s.l.) are about 2 km away from the Scirca spring to the north and to the south, respectively. Their recharge area is separated from that of Scirca spring by major lineaments, representing Jurassic faults, and their recharge area is isolated from that of Scirca spring (Valigi et al. 2012). The springs emerging on the eastern slope of Cucco Mountain are also independent from the Scirca spring due to both tectonic and stratigraphic reasons (Valigi et al. 2012). There are no withdrawals within the recharge area, while the Scirca spring is tapped for drinking purposes.

Geo-structural surveys

To characterize the geo-structural context and to obtain a map of surface karst features (e.g., dolines and swallow holes), considered as point infiltration zones (Ravbar 2013), a detailed geological survey of the Cucco Mountain area was performed. Field mapping was based on the existing 1:10,000 scale geological maps produced by the Umbria and Marche regions (Regione Marche 2002; Regione Umbria 2015). Fieldwork was primarily focused on updating the existing dataset and adding details on the structural geology and karst features in the area. In addition, based on both existing and original data, five geological sections were constructed for both across and along the main Cucco Mountain anticline to obtain a coherent image of the subsurface. Three geological sections follow a rough NE–SW orientation, while the remaining two are NW–SE-oriented, so that the first set is perpendicular to the second. The sections were drawn to clarify the tectonic and stratigraphic boundaries of the geological formations, and to identify how the structural configuration influences the hydrogeological setting. The 10-m-resolution TINITALY Digital Elevation Model (DEM) v1.1 (Tarquini et al. 2023) was used as the basemap for computing the topographic profiles, while geological information was obtained from the 1:10,000 scale Umbria and Marche regions' geological maps, which were merged after verifying the contacts between the geological formations and conducting a cross-check of the available data following the field surveys. The geological cross sections were then imported in Visual KARSYS 3D (Malard et al. 2019) to obtain a comprehensive 3D visualization of the geological setting and to delineate the Scirca spring recharge area.

Hydrological data

Data from three thermo-pluviometric stations located at different elevations (Table 1) were analyzed to assess precipitation and temperature within the study area (Fig. 1).

Stations S1, S2, and S3 provided daily cumulative rainfall and average temperature data for the period from 01 January 2010 to 31 December 2022, sourced from the Hydrographic Service of the Umbria Region (SIR—Regione Umbria—Servizio idrografico) and from the Civil Protection Agency of Marche Region (SIRMIP—Regione Marche—Protezione Civile).

Despite the mountainous environment, daily snow depth was only measured at (S3), which is also the station with the highest elevation (1092 m a.s.l.). All the time series were

Table 1 Hydrologic monitoring points

Station	Coordinates east; north (ETRS89 UTM33N)	Elevation (m a.s.l.)	Distance from the study area (km)	Parameters	Measuring period (start/end)	Missing data on daily basis (%)
S1	12.79; 43°1'	535	30	Rainfall, temperature	Jan 2010/Dec 2022	1.6
S2	12°65'; 43°4'	688	7	Rainfall, temperature	Jan 2010/Dec 2022	0.7
S3	12°73'; 43°3'	1092	0	Rainfall, temperature, snow depth	Jan 2010/Dec 2022	1.9
Scirca spring	12°43'; 43°21'	575	-	Discharge	Jan 2010/Dec 2022	10

examined for missing data, ensuring gaps did not exceed 10% of the total duration (Table 1).

These stations were chosen because they were relatively close to the study area, providing a reference; hence, daily rainfall and temperature data were aggregated to determine the monthly rainfall and temperature. Monthly temperature data were used to define mean monthly temperature in S1, S2, and S3.

As for rainfall, in this context, it is important to remark that it is quite frequent, at least in the Apennines, to have difficulties in the estimation of precipitation falling in solid form (i.e., snow) since the snow depth stations have a random spatial distribution, and there are no snowpack density measurements sites to apply a site-specific water-equivalent snowpack thickness ratio.

In this study, the snow contribution to the aquifer recharge was evaluated by ground-based observation in a barycentric position of the recharge area (S3) by summing the daily increase of snow cover recorded by means of an ultrasonic snow-depth gauge. Then the snow depth was converted into snow water equivalent (SWE) at the annual scale to minimize the error associated with the snow density variability that can occur during the snowy periods (Fayad et al. 2017).

Since no manual sampling or snow-pillow network is operational in the study area, the 10-to-1 rule was adopted (Judson and Doesken 2000), which assumes that the snow ratio, calculated as the density of water (1000 kg/m^3) divided by the density of snow (presumed to be 100 kg/m^3), equals 10:1. According to this rule, 10 mm of snowfall is supposed to produce 1 mm of liquid water. Despite the caveats regarding its limitations, the 10-to-1 rule remains in widespread use when dealing with hydrogeological studies focused on groundwater budget and it is in accordance with the most recent literature regarding the snow hydrology of the Apennine Mountains (Lorenzi et al. 2022; Rusi and Di Giovanni 2025).

The cumulative snow depth was calculated on a monthly scale for the snow-recording station (S3) only by summing the daily increase of snow cover. Specifically, for each ultrasonic snow-depth gauge, the corresponding total new snow Δh was determined following Eq. (1)

$$\Delta h = \sum_{t=1}^{m} (\Delta h_t) \tag{1}$$

where m is the total number of days with snowfall in each snowy month, and Δh_t corresponds to the depth of new snow on day t. Indeed, the new snow is defined as the depth of freshly fallen snow deposited over a standard observation period (i.e., 24 h) (Senese et al. 2018). The daily snow depth measurements recorded by the snow-depth gauge were analyzed to calculate the difference between that and the former reading. A positive difference of at least 1 cm indicates new snowfall. To ensure accuracy, all data underwent rigorous quality control measures to manually eliminate under- or over-measurements, remove outliers and invalid values, and filter out potential noise.

Once the monthly snowfall in S3 was defined for each snowy month by using Eq. (1), its value was added to the rainfall amount recorded in the same month in S3. A new monthly total precipitation time series (2010–2022), accounting for the snowfall contribution, was therefore generated for S3.

The mean annual cumulative precipitation in S1, S2, and S3 was then defined by summing all mean monthly precipitation values.

Two different elevation vs. mean annual precipitation relationships were therefore determined from the data available from monitoring stations S1, S2, and S3. The first relationship does not take into account the snow contribution in S3 and consists of the linear regression of elevation vs. mean annual rainfall (Pr) values at S1, S2, and S3.

The second relationship accounts for the snow contribution in S3. A new monthly total precipitation time series was generated in this station by adding to the recorded monthly rainfall the contribution of the snow cover. This new time series was used to determine the mean annual total precipitation in S3 (Pr*). The second elevation vs. mean annual precipitation linear relationship was defined by using the original mean annual rainfall (Pr) at S1 and S2 and the Pr* at S3.

The comparison between the two relationships allowed for the estimation of how the snow contribution to total precipitation increases with elevation and at what elevation the snow contribution becomes significant. The relationship accounting for Pr* at S3 was then used to spatially distribute the overall annual precipitation over the recharge area by means of the 10-m-resolution TINITALY Digital Elevation Model (DEM) v1.1 (Tarquini et al. 2023).

The natural discharge of the spring is continuously measured by the Umbria Environmental Protection Regional Agency (ARPA) since 2007, on a daily timescale. The spring has a variable discharge regime, with an average annual discharge of 211 l/s, and minimum and maximum daily discharge of 48.6 l/s and 463.5 l/s, respectively (2010–2022 period) (see Fig. S1 of the electronic supplementary material (ESM)).

Groundwater budget calculations

Thornthwaite–Mather

The monthly hydrological balance of the Scirca spring for 2010–2022 was computed using the Thornthwaite–Mather method using the monthly temperature and monthly rainfall measured at S1, S2, and S3. Although this approach dates back several decades, it has been applied in numerous case studies across central Italy, particularly within the Apennines, demonstrating its robustness and relevance in hydrogeological research to assess groundwater recharge and water availability in karst aquifers (Fiorillo et al. 2019; Di Curzio et al. 2022). The method's efficacy in capturing seasonal variability and its compatibility with readily available climatic datasets have contributed to its continued use, even in areas with complex hydrogeological characteristics. In the context of the Apennines, the Thornthwaite–Mather approach has proven valuable in quantifying water balances on a monthly scale, providing essential insights for water resource management and sustainability assessments in hydrologically sensitive areas (Rossi et al. 2022).

As the monthly rainfall values (Pr) were available for the 2010–2022 interval at S1, S2 and S3, the monthly actual evapotranspiration (AET) and water surplus (WS) were calculated at each station, exploiting the WaterbalANce Web App (Mammoliti et al. 2021). The snow contribution recorded at S3 was then added to the WS determined for this station. This approach implies that the snow cover is considered to entirely contribute to WS, as suggested by Fayad et al. (2017).

The scheme of Fig. 2 illustrates the process for determining monthly WS on the basis of the Thornthwaite–Mather method.

As a first step, the method determines the monthly potential evapotranspiration (PET) starting from monthly temperature (T_m) and rainfall (Pr). The influence of the day duration on the evapotranspiration process, depending on the latitude (LAT) and on the month of the year (*i*), is taken into account by means of appropriate correction coefficients, as proposed by the Thornthwaite–Mather method.

It is known that the soil moisture storage capacity (SM) influences monthly WS. In the Cucco Mt. Massif, despite the karst environment, the soil spans over the entire area, although its thickness is rather low. Therefore, SM was chosen equal to 100 mm, consistent with the latest technical and scientific literature on similar lithologic contexts (Mammoliti et al. 2021; Cusano et al. 2024).

By using the above-described procedure (Fig. 2), the monthly WS in S1, S2, and S3 was generated starting from the Pr recorded at these stations. The monthly WS values at S1, S2, and S3 were aggregated at an annual scale and a first linear relationship between elevation and mean annual WS was determined.

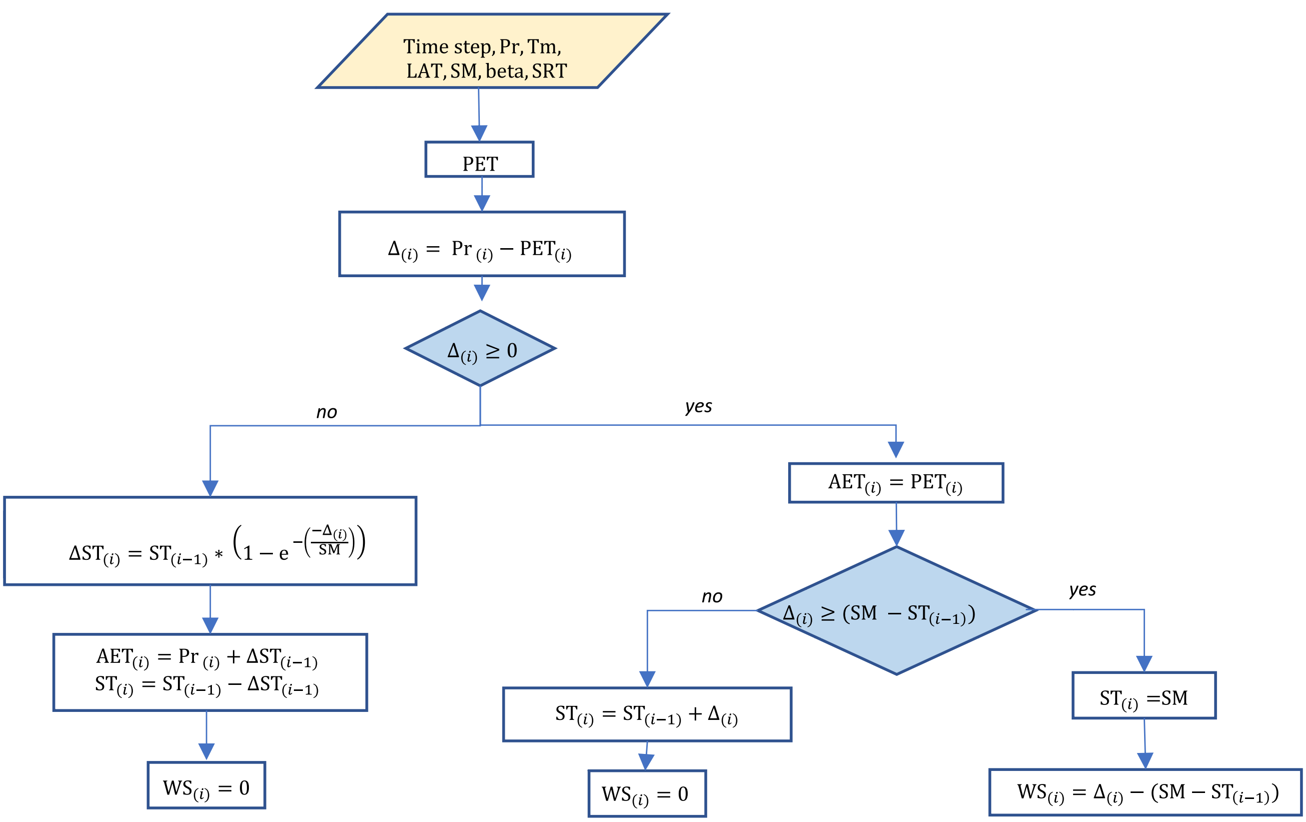

Fig. 2 Workflow of the WaterbalANce code. Pr monthly rainfall (mm), Tm mean monthly temperature (°C), LAT latitude (°), SM soil moisture storage capacity value (mm), PET monthly potential evapotranspiration (mm), *Δ* Pr-PET (mm), AET monthly actual evapotranspiration (mm), ST monthly soil moisture (mm), WS monthly water surplus (mm) (modified after Mammoliti et al. 2021)

Afterwards, the snowfall recorded at S3 was added to the WS calculated at this station, therefore generating a higher WS, named WS*, associated with S3. This procedure implies that snowfall was assumed to entirely contribute to WS and that AET associated with precipitation in the form of snow is considered nil. This is consistent with the observation that, in winter, PET is negligible since, for the evaporation component, is mainly linked to the sublimation process. As for transpiration, both grassland and deciduous (non-evergreen vegetation), which are found in the recharge area, are often dormant so that they do not transpire and soil water does not evaporate as it is insulated by snow. Therefore, AET is close to nil (Ning et al. 2020).

A second elevation vs. WS linear relationship was determined by using WS at S1 and S2 and WS* at S3.

As the final goal of this study was to evaluate the water budget at a mean annual scale, and to compare the results with those obtained for the Scirca spring at the same time scale with other traditional methods (Fronzi et al. 2025), the monthly data were aggregated on a solar-year basis.

The comparison between the elevation vs. WS and WS* relationships allowed for the estimation of the elevation starting from which the snow contribution to total WS becomes significant, and how the contribution of snowfall to WS increases with elevation.

The relationship accounting for the snow contribution to the water surplus was subsequently used to spatially distribute the total mean annual WS* over the recharge area by means of the 10 m-resolution TINITALY Digital Elevation Model (DEM) v1.1 (Tarquini et al. 2023).

Recharge to the Scirca spring (Re) corresponds to the portion of WS* which generates effective infiltration. This fraction is usually determined as a function of lithologies, to which a potential infiltration coefficient (PIC), in the range of 0–1 is attributed (Celico 1988; Viaroli et al. 2018). The highest values of infiltration coefficient are generally associated with highly developed karst systems, where infiltration is largely independent of the topographic and tectonic characteristics of the area. In such systems, the infiltration rates are known to be close to the water surplus, or even to precipitation amounts in specific time intervals when evapotranspiration is very low (Lorenzi et al. 2022). In the Scirca spring recharge area, the Calcare Massiccio formation, within which the highly developed karst system is found, outcrops widely. Moreover, the Maiolica Formation is highly fractured, and the tectonic lineaments related to extensional tectonics are expected to act as preferential infiltration zones. The runoff possibly occurring in the small areas where formations with higher marly/siliceous components (e.g., Bugarone and Calcari Diasprigni) outcrop is confined within the recharge area and, due to topography, is directed toward highly permeable formations and/or toward highly fractured areas. Therefore, the PIC value over the entire Scirca recharge area approaches the maximum value (1), which is usually associated with karst formations.

APLIS

The APLIS method (Andreo et al. 2008) was specifically designed for carbonate karst rocks to estimate the aquifers recharge rate (*R*), which represents the percentage of rainfall contributing to the recharge. *R* is calculated by a combination of five physical parameters, namely: altitude (*A*), slope (*P*), lithology (*L*), preferential infiltration zones (*I*), and soil type (*S*), according to the following equation, Eq. (2):

$$R(\%) = (A + P + 3L + 2I + S)/0.9 \tag{2}$$

For each parameter, a numerical value ranging between 1 and 10 is assigned, except for preferential infiltration zones (*I*) that, in the original APLIS method, can only take the values of 10 or 1. The value of 10 is usually attributed to the areas where the main infiltration landforms (e.g., dolines, swallow hole, sinkholes) are recognized, while the value of 1 is given to the areas without visible infiltration landforms. However, in recent years, some authors have applied different scales in the Gran Sasso area (central Italy) for this parameter, considering that the mature karst is often not totally developed where the carbonate rocks are covered by Quaternary deposits (Petitta et al. 2022). In this case, an intermediate value of 5 has been attributed based on expert judgment of areas with the widespread occurrence of dolines (Andreo et al. 2021). In addition, the parametric formulation of the original APLIS method has been modified over the years to include a correction parameter (Fh) that considers the exposure of the aquifer at the topographic surface. Specifically, values of Fh = 1 are applied where the aquifer crops out, while other parts are indicated by a value of Fh = 0.1.

Only a few recent works (Entezari et al 2020; Errahmouni et al. 2022; Tadmouri et al. 2024) incorporate the presence of faults in the APLIS method, considering that tectonic lineaments play a not negligible role in groundwater recharge and flow due to their related fracture and joint network involving their damage zone (Fronzi et al. 2020, 2021; Cambi et al. 2022; Labry et al. 2025; Petrella et al. 2025). In this study, the original APLIS method (Andreo et al. 2008) was modified following Errahmouni et al. (2022) and the *R* was calculated using Eq. (2), expressing the parameter *I* as a function of *C*, *F*, and *P* as follows, Eq. (3):

$$I = C + F + P \tag{3}$$

where *C* is a coefficient that may assume the value of 0 or 1 depending on the lithology's capacity to develop surface karst landforms. In our case, the value of 1 was assigned to the CM–Co complex, characterized by clear surface karst features, while the value of 0 was assigned to all other hydrogeological complexes, without evident karstic forms. The parameter *F* varies according to the distance from tectonic lineaments. Specifically, buffer zones of 50, 150, 300, and > 300 m from faults are respectively classified with *F* values of 10, 6, 2, and 0, as proposed by Entezari et al. (2020). *P* is the slope as interpreted in the original APLIS method (Andreo et al. 2008). Parameter *I*, as calculated following Eq. (3), was therefore rescaled in a range of 0–10.

When using the modified APLIS method, a calibration process was run with the aim of defining a combination of parameters capable of returning a recharge value (Re) that is close as possible to the mean annual discharge of the Scirca spring.

Results

Reconstruction of the spring recharge area

The spring recharge area was defined on the basis of five cross sections (Fig. 3), three of which (AA', BB', and CC') were perpendicular to the anticline axis and two parallel to it (DD' and EE'). A 3D view of the sections is shown in Fig. 3. The cross sections allowed for the definition of the structure of the anticline, whose core is represented by the reduced Jurassic sequence, separated by Jurassic normal faults from the deeper basinal area where the complete succession outcrops (see sections BB', CC', DD', and EE'). The easternmost Jurassic fault, extending to the south beyond the spring recharge area along a N–S direction, represents an important geological, topographic, and hydrogeological limit, and corresponds to the eastern boundary of the Scirca spring recharge area. The northeast limit of the recharge area also corresponds to outcropping Jurassic faults, while the northwest boundary was defined by topography and based on the attitude of the geological formations. Eventually, the western boundary corresponds to the outcrops of the low-permeability MF hydrogeological complex, such as the southwest border. The south-eastern limit was based on topographic criteria. The recharge area so defined is 7.2 km^2 wide (Fig. 3) so that the mean annual discharge of the Scirca spring expressed in millimeters per year equals 929 mm/year. The recharge area altitude ranges between the elevation of Scirca spring (575 m a.s.l.) and the Cucco Mountain peak (1562 m a.s.l.), with an average elevation of 1101 m a.s.l. The average slope of the recharge area is 29°, with the steepest zones located in the north-eastern sector, with a marked sub-vertical morphological break involving the Calcare Massiccio. Two soil types have been recognized within the Scirca spring recharge area. The predominant type, covering almost the entire area (7.0 km^2), consists of Cambisols, while the remaining 0.2 km^2 are characterized by Leptosols. Soil type data were obtained from the ISRIC (2015) World Soil Information Service (WoSIS version 2.0) (Ribeiro et al. 2015) and were integrated with available in situ surveys.

Hydrological data analysis

The analysis of temperature and rainfall time series allowed to determine the main climatic parameters, namely temperature and precipitation, at an average monthly and annual scale.

The dotted green line of Fig. 4 shows the elevation vs. mean annual rainfall relationship determined by using the rainfall data at S1, S2, and S3 (Pr at S3). The continuous yellow line shows the relationship determined by taking into account the contribution of snowfall to total precipitation (Pr*) at S3. It can be clearly observed that both relationships are linear, and the two lines are virtually superimposed on each other at elevations lower than

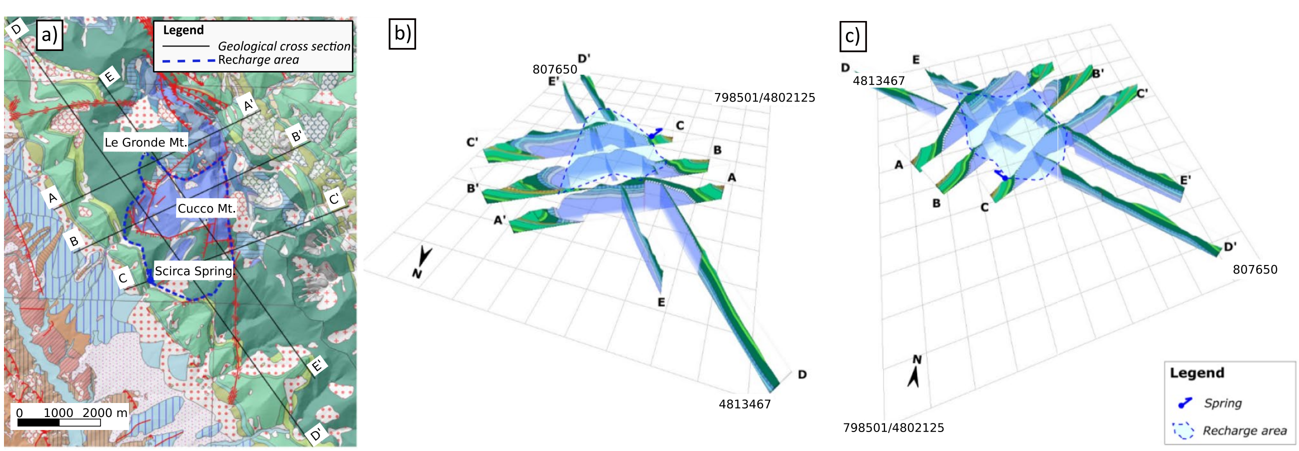

Fig. 3 Newly identified recharge area for the Scirca spring, with traces of cross sections (**a**) and 3D overview of the hydrogeological framework of the Cucco Mt. Massif, derived from the geological cross sections (**b** and **c**). *Colors* refer to the legend in Fig. 1

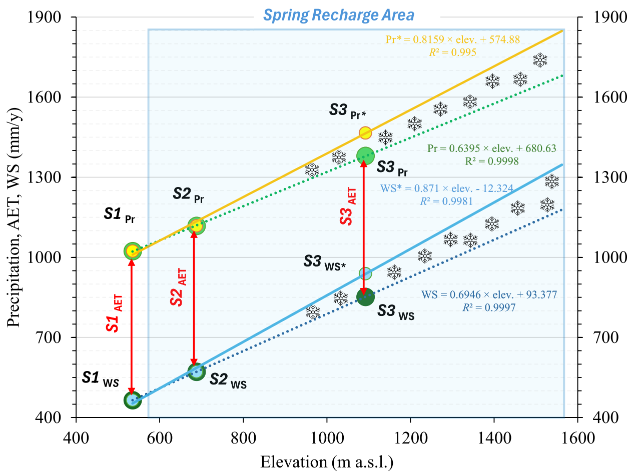

Fig. 4 Elevation vs. precipitation relationships when considering only rainfall (Pr) (*dotted green line*), and when considering the snow contribution (Pr*) in S3 (*continuous yellow line*). Elevation vs. WS relationships when considering WS as determined by WaterbalANce for S1, S2, and S3 (*dotted blue line*) and when adding the contribution of snow at WS in S3 (WS*) (*continuous blue line line*). The *vertical arrowed red bars* represent the mean annual actual evapotranspiration (AET) generated by WaterbalANce at stations S1, S2, and S3

about 700 m a.s.l. By interpreting these results, it can be assessed that, in this area, the snow contribution to total annual precipitation becomes significant only at elevations higher than 700 m a.s.l. and accounts for a maximum of 170 mm/year (about 10% of annual precipitation). This result is consistent with the temperature data which show that the mean monthly temperatures recorded at lower elevations (S1 and S2) are significantly higher than 0 also in winter months. In fact, the average monthly temperature at S1 (535 m a.s.l.) in the winter months (Dec-Jan-Feb) is 5.6 ± 0.8 °C, while in S2 (688 m a.s.l.) is 4.9 ± 0.8 °C. On the contrary in S3 (1092 m a.s.l.) the average monthly temperature of winter months is 1.9 ± 0.9 °C.

Figure 5a shows the distribution of Pr* over the recharge area determined by spatializing the data with elevation by the 10-m-resolution TINITALY Digital Elevation Model (DEM) v1.1 (Tarquini et al. 2023).

Groundwater budget calculations

Thornthwaite–Mather

The monthly WS values generated by the WaterbalANce at S1, S2 and S3, and aggregated at annual scale to determine the mean annual WS, are represented by the dark blue dots in Fig. 4. The vertical arrowed red bars in Fig. 4 represent the mean annual actual evapotranspiration generated by WaterbalANce at S1 S2 and S3 which was spatially distributed over the recharge area (Fig. 5b) by means of the 10 m-resolution TINITALY Digital Elevation Model (DEM) v1.1 (Tarquini et al. 2023). The dark blue dotted line in Fig. 4 shows the linear relationship among elevation and mean annual WS determined by WaterbalANce.

The mean annual snowfall determined in S3, entirely added to the WS calculated in S3 by WaterbalANce, allowed to determine WS* in S3 (pale blue dot in Fig. 4) and a second linear relationship between elevation and total WS* (pale blue continuous line in Fig. 4), accounting for snow contribution.

This last relationship was used to spatialize the total WS* across the Scirca spring recharge area. As observed for precipitation, the two lines are superimposed to each other at elevations lower than about 700 m a.s.l.. This is consistent

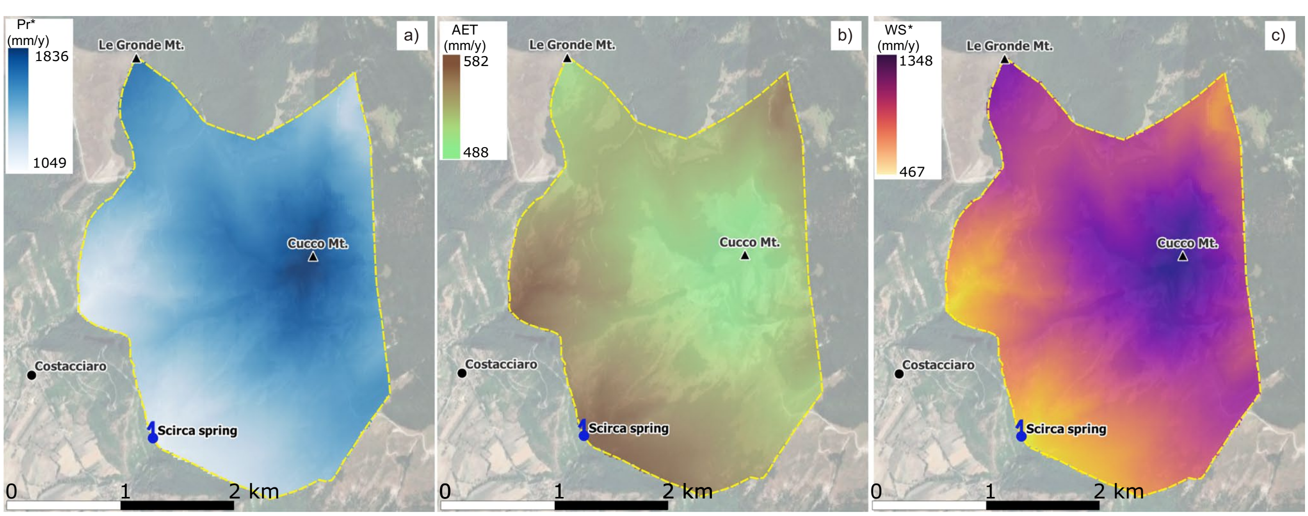

Fig. 5 Spatial distribution of: **a**) mean annual Pr*, **b**) mean annual AET, and **c**) mean annual WS*as a function of elevation

with the fact that the snowfall, entirely converted into water surplus (WS*), was found to contribute to total annual precipitation only at elevations higher than 700 m a.s.l. (see the ***Hydrogeological data analysis*** section), with a maximum contribution of 170 mm/year, (14% of annual water surplus), at the highest elevation.

According to the relationship determined by using WS* at S3 (pale blue continuous line in Fig. 4) the annual total WS* ranges between 467 and 1348 mm/year across the recharge area, with a mean value of 947 mm/year. Such a value is comparable with that determined by Fronzi et al. (2025) by using the Turc method. This indicates that the parameter SM of the Thornthwaite–Mather method was set properly and confirms that both the Turc and Thornthwaite–Mather methods provide reliable results when used in central Italy. Figure 5 shows the spatialization of total precipitation (Pr*) actual evapotranspiration (AET) and total water surplus (WS*) on the Scirca spring recharge area.

Given the areal extent of the recharge area (7.2 km^2) WS* corresponds to an average discharge of 216 l/s which roughly matches the measured average discharge of the Scirca spring (212 l/s). This indicates that the whole *WS** contributes to the infiltration so that, according to the Thornthwaite–Mather method, Fig. 5c also represents a recharge map. This means that the PIC is approximately equal to 1, as already observed by Fronzi et al. (2025). Such a high value corresponds to the upper limit of PIC, associated with karstified limestones (Celico 1988), in line with the geological context of the study area. Although part of the spring's recharge area consists of geological formations made up of fractured and/or dolomitic limestones, the significant development of epigean and hypogean karst features, along with the presence of major tectonic discontinuities, supports the hypothesis that all WS* contributes to effective infiltration, in turn feeding the Scirca spring. This hypothesis is further corroborated by the nearly complete absence of surface watercourses/streams within the newly identified recharge area. This result also confirms that the recharge area was correctly defined and that the system has no significant groundwater exchanges with external water bodies.

APLIS

The calibration process run to define a combination of the five APLIS parameters capable of returning a mean annual recharge (Re) as close as possible to the mean annual discharge of the Scirca spring (929 mm/year), consisted of 20 iterations. The parameter values were spatially distributed over the recharge area as shown in Fig. 6. Parameter *A* ranges between 2 and 6 since the altitude of the newly identified recharge area spans from 575 and 1562 m a.s.l. The value of *P* spans from 1 to 10, assuming all the possible values according to the original APLIS method. As concerns the *L* values, according to the ratings proposed by Andreo et al. 2008, a value of 10 was assigned to the karstified limestones MAS, COI, and to the highly permeable slope deposits (not rated by Andreo et al. 2008). A value of 9 was assigned to the highly fractured pelagic limestone MAI, 6 to the fissured limestone BU, and 2 to the POD and CDU, which have a significant marly component. The parameter *I* expressed as described in Eq. (3), according to the modified APLIS method, assumes the discrete values of 10, 9, and 8 by moving from the faults cores towards the faults damage zones, while in the far most areas with respect to the fault system *I* assumes the values of 4 and 1. Eventually, the parameter *S* assumes the discrete values of 6 and 10, for Cambisols and Leptosols respectively, as proposed, as well, by the original APLIS method.

It can be observed that higher values for the Infiltration (*I*) parameter determined by the modified APLIS method (Fig. 6d) are concentrated along the fault zones, where the majority of surface karst landforms are also found.

The annual recharge flux (*R*) corresponding to the selected combination of parameters is 915 mm/year, corresponding to 62% of mean annual rainfall and is slightly lower than the overall water surplus (WS*) determined starting from the Thornthwaite–Mather method (see the ***Thornthwaite–Mather*** sub-section of the ***Results*** section).

The recharge was spatialized over the Scirca spring recharge area by combining the five selected parameters in a GIS environment according to Eq. (2) and by multiplying the obtained rated layer by the spatialized precipitation layer (Fig. 5a). This allowed obtaining a detailed infiltration map (Fig. 6f), in which zones with higher and lower infiltration rates can be distinguished.

A further check of the calibrated parameters was done using the modified APLIS method in conditions other than the annual average. The method was used, with the same parameters, to generate the Scirca spring annual discharge for the wettest and the driest years, selected on the basis of the annual discharge. In the 2010–2022 interval, the highest annual discharge (283 l/s, corresponding to 1238 mm/year) occurred in 2013, while the lowest (168 l/s, corresponding to 736 mm/year) occurred in 2017. The annual precipitation for these years was determined starting from the rainfall data recorded at S1, S2, and S3. The contribution of snow was added to rainfall at S3 for the year 2013 only, as it was found that in 2017, due to the extremely dry conditions, no snowfall occurred. For the wettest year, the output of the modified APLIS method was 1247 mm/year (corresponding to 284 l/s as average annual discharge), quite close to the measured value. As for the dryest year, the modified APLIS output was 783 mm/year (179 l/s), about 7% higher than the measured value.

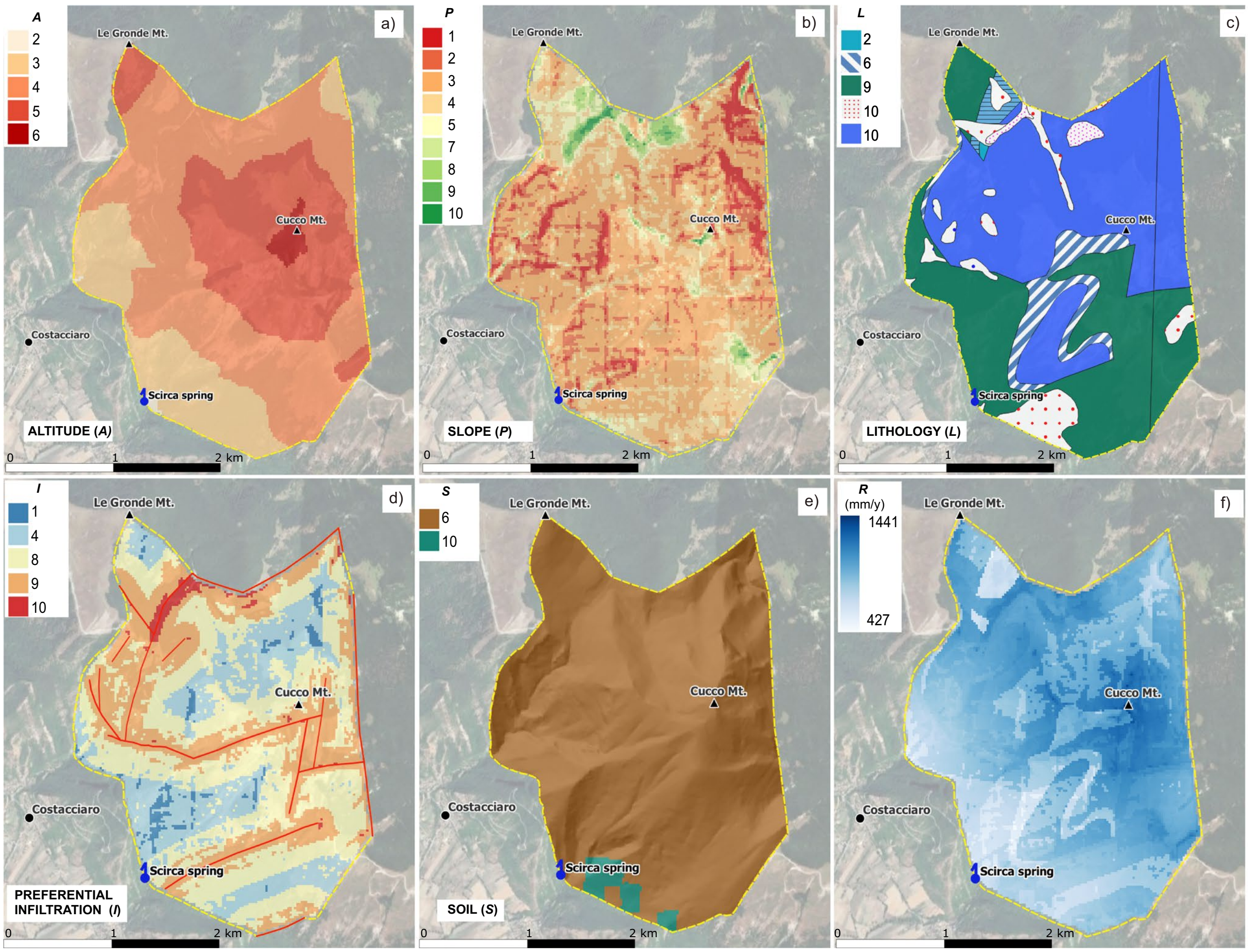

Fig. 6 Spatialization of the APLIS parameters **a**) altitude (elevation), **b**) slope, **c**) lithology, **d**) preferential infiltration zones, **e**) Soil type, and **f**) Recharge map according to APLIS

Discussion

While discussing the results, it must be emphasized that the estimation of spring recharge, both when using traditional and parametric methods, must rely upon a detailed reconstruction and characterization of the spring recharge area, aquifer geometry, and the lithological and geomorphological features, based on in situ geological and hydrogeological surveys. These surveys help to minimize errors associated with the selection of the parameters used in the methods.

In view of this, the recharge area of the Scirca spring was newly delimited through a detailed geometric reconstruction based on geological and geo-structural surveys. This approach provided a robust framework for contextualizing and validating recharge estimates, which were defined only later, so that the two processes of recharge area definition and infiltration estimates are independent.

The newly defined recharge area is about 9% larger (7.2 km^2 vs. 6.6 km^2) than the one previously delimited by Dragoni et al. (2013). On the contrary, it is about 8% smaller (7.2 km^2 vs. 7.8 km^2) than the one defined by Tamburini and Menichetti (2020). Although these differences are small, the recharge area was calculated for the first time based on an accurate geo-structural study, built on five cross sections crossing with each other, and supported by the 3D reconstruction of the geological setting. The newly defined recharge area is also consistent with the results of the former artificial tracer tests conducted in the area (Forti et al. 2003; Menichetti et al. 1988), as shown in Fig. 7.

The aquifer recharge was quantified using both traditional and parametric methods, with particular attention given to fault zones and karst infiltration landforms. A comparative analysis of the Thornthwaite–Mather results, against the annual-scale results recently published by Fronzi et al.

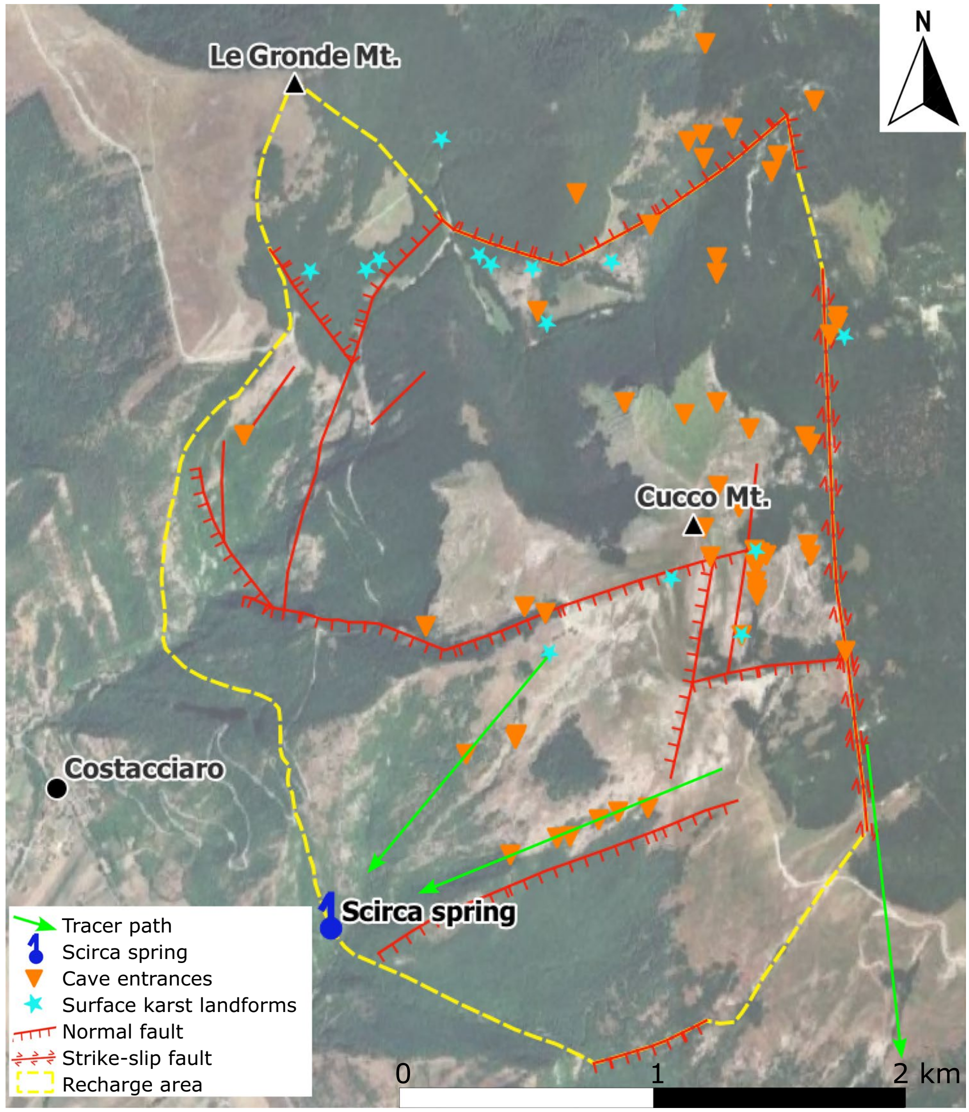

Fig. 7 Karst landforms (dolines and cave entrances) and fault zones in the Scirca spring recharge area, with artificial tracer tests results conducted in the study site by Menichetti et al. (1988)

(2025), demonstrated their complementarities and mutual reliability for the mountain ridges of central Italy.

It is important to emphasize that traditional groundwater budget methods estimate actual evapotranspiration (AET) based on precipitation and temperature data, to derive water surplus (WS), meant as the difference between precipitation and actual evapotranspiration. These methods, therefore, do not directly provide the value of effective infiltration. Conversely, the parametric methods, such as the APLIS, in both its traditional (Andreo et al. 2008) and modified versions (Enterazi et al. 2020; Errahmouni et al. 2022; Tadmouri et al. 2024), directly calculate recharge rate (*R*) as a percentage of precipitation, based on physical parameters that do not include temperature. Therefore, such methods do not allow to directly estimate evapotranspiration and, consequently, water surplus.

Both methods have common weaknesses deriving from the fact that they rely upon an accurate estimate of precipitation, which can be difficult to obtain in mountain areas, particularly when a not negligible fraction of it comes in solid form, and the correct reconstruction of the recharge area.

In the study site, the snow contribution to the recharge becomes significant starting from 700 m a.s.l. and may account for a maximum of 170 mm/year (about 10% of annual precipitation) and 120 mm/year (14% of annual water surplus), at the highest elevation. Despite increasing recognition of the role of snowmelt in sustaining water resources, significant limitations persist in understanding its contribution to groundwater recharge in the Italian Apennines. These include sparse and unevenly distributed observation networks, the lack of integrated snow-groundwater modelling frameworks, and the inherent complexity of the region's hydrogeology, particularly in karst and fractured rock systems.

Apart from these common weak points, whose weight varies depending on the available data, the two approaches have different drawbacks, as the traditional methods, while allowing the estimation of WS, do not consider many factors that influence the repartition between runoff and effective infiltration. In fact, the infiltration rate is linked only to lithology, using the PIC. On the contrary, the parametric methods, and particularly the modified APLIS method used in this work, take into account other important factors influencing infiltration, such as topography, soil type, karst development, and tectonic lineaments. Nonetheless, they give no indication concerning the fraction of rainfall, which contributes to evapotranspiration and/or runoff. While traditional PET estimation approaches like Thornthwaite–Mather and Turc methods offer robust recharge estimates under appropriate meteo-climatic data availability, they inherently lack the spatial resolution and structural sensitivity provided by parametric approaches. The modified APLIS method complements these approaches by integrating tectonic and geomorphic features directly into recharge estimation, offering a more physically grounded depiction of subsurface flow processes. This dual-method framework strengthens confidence in the estimated recharge values and reveals how complementary the two methods are when applied in tandem, particularly in complex mountainous karst settings where recharge is controlled by both climatic and structural variables.

Therefore, the simultaneous use of both methods to assess the effective infiltration represents a cross-check, allowing for overcoming the specific limitations of each approach.

In this case, both traditional methods used/inherited to assess the recharge for the Scirca spring (Thornthwaite–Mather and Turc) estimated an actual evapotranspiration (559 and 546 mm/year) which accounts for slightly less than 40% of total precipitation. Such values yield a WS very close to the average annual discharge of the spring measured in the period 2010–2022, suggesting that the surface runoff is nearly negligible and that PIC approaches 1 (Table 2). This was expected, as reported in the ***Groundwater budget calculations*** section, and it is consistent with the scarce development of the surface water pattern and with the geology of the area. In fact, the highly karstified Calcare Massiccio Formation outcrops over more than half the recharge area, with the remaining part occupied mainly by the highly fractured Maiolica formation. The runoff possibly occurring over the formation with a higher marly/siliceous component (Bugarone and Calcari Diasprigni) is confined within the recharge area and, due to topography, is directed toward highly permeable formations and/or toward highly fractured areas.

The results from the APLIS method align with those provided by traditional methods, suggesting that the mean annual recharge amount (915 mm/year) is slightly over 60% of precipitation. This implies that about 40% of precipitation may be lost due to evapotranspiration and/or runoff. As this percentage matches the AET calculated using traditional methods, the results of traditional and parametric methods here used are consistent with each other when assuming the runoff is negligible, as suggested by geological and hydrological considerations. Results show that in this area both approaches give the same results in terms of mean annual total recharge, suggesting that any of them can be used to evaluate mean annual recharge in Northern Apennines and that the choice between the two can be driven by data availability.

The same type of cross-check in other areas could indicate whether these approaches can also be used interchangeably in different regions.

Nonetheless, a significant difference in the results of the two methods can be observed when looking at the recharge pattern across the spring recharge area (Fig. 8).

The map of Fig. 8a clearly shows that, in the specific case of Scirca spring recharge area, all over which the PIC approaches 1, the distribution of recharge evaluated by Thornthwaite–Mather is only linked to elevation, and does not account for any other physical parameter. On the contrary, the recharge map obtained by using the modified APLIS method (Fig. 8b) makes it evident that areas with higher infiltration rates are not only associated with higher elevations. When applying the modified APLIS method to

Table 2 Overview of the water budget results obtained for the Scirca spring

Groundwater budget method	Pr (mm/year)	*T* (°C)	AET (mm/year)	WS (mm/year)	Area-weighted mean PIC(-)	Computed recharge (mm/year)	Discharge (mm/year)	Reference
Turc	1478	10.3	546	932	1	932		Fronzi et al. 2025
Thornthwaite–Mather		10.3	559	947 [b]	1	947		This study
APLIS	1474[a]					915		This study
Measured spring discharge							929	This study

[a]Rainfall + Snowmelt (Pr*)

[b]WS + Snowmelt (WS*)

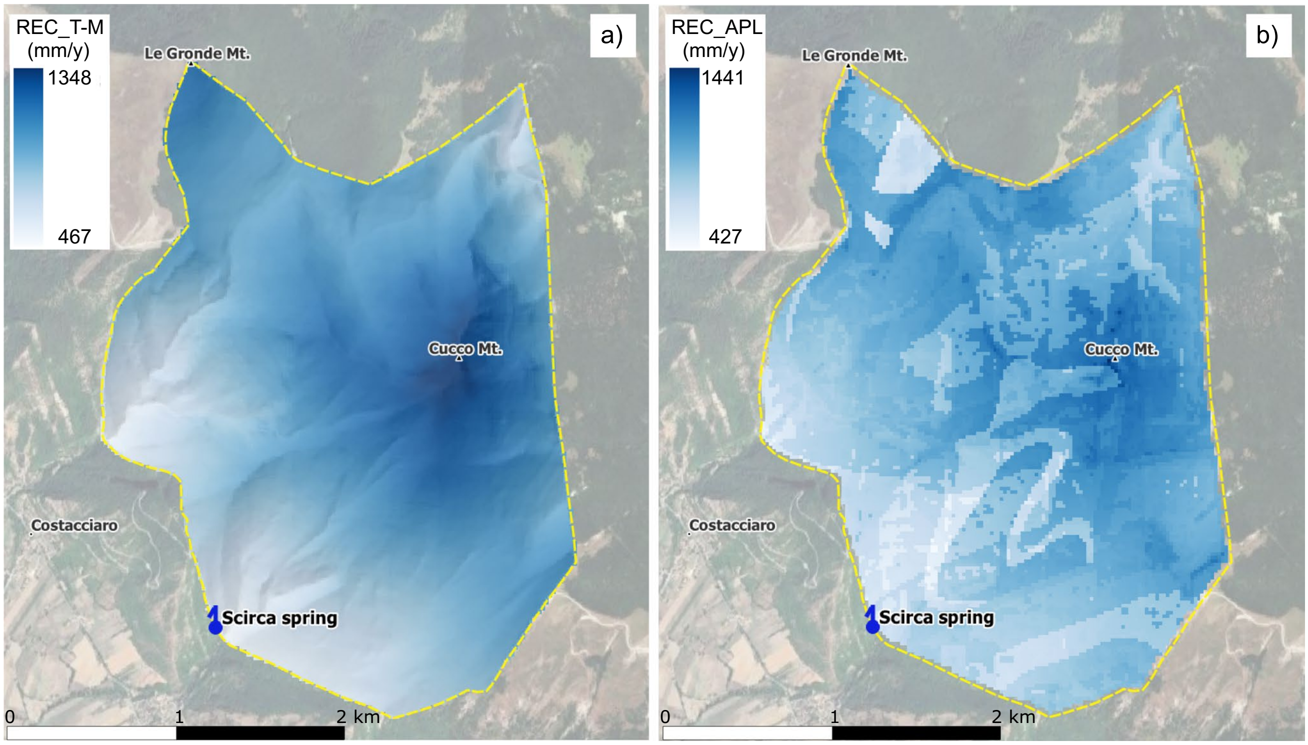

Fig. 8 Maps of: **a**) Recharge distribution according to Thornthwaite–Mather (REC_T-M), **b**) Recharge distribution according to APLIS (REC_APL)

the Scirca spring recharge area, the influence of the lithology factor is marginal as in the majority of the area the *L* parameter is in the interval 9–10 (Fig. 6c), consistently with what was found when using Thornthwaite–Mather (PIC approaches 1). Soil type is also uniform in the whole recharge area (Fig. 6e). This implies that, besides altitude (Fig. 6a), preferential infiltration zones related to highly tectonized areas (Fig. 6d) and slope (Fig. 6b) are the factors mainly influencing effective infiltration. This is reflected in the recharge map of Fig. 8b. The use of a modified APLIS method is therefore beneficial when trying to determine the distribution of effective infiltration, as it links it to important physical parameters related to the territorial characteristics. This can be of great importance when defining the strategies to protect groundwater resources of strategic importance, such as those of the Scirca spring.

The application of the APLIS method in its modified version emerged as a promising approach for evaluating recharge in fractured carbonate aquifers, as it allows to account for the strong influence of fractures and tectonic lineaments. In this specific case, it is observed that surface karst landforms and caves entrances are mainly found in correspondence of fractured and faulted zones related to extensional tectonics (Fig. 7).

This makes it evident that in karst environments, where normal faults and karst structures can be superimposed on each other, the infiltration process is strongly favored, so that, with respect to karst zones unaffected by extensional tectonics, a higher infiltration rate is observed, which in this case turns into a negligible runoff. Indeed, when using the original APLIS method on the Scirca spring recharge area (Fronzi et al. 2025), by applying all the same parameter values but for parameter *I* (infiltration landforms), the computed recharge is slightly lower than that determined by the modified method (897 vs. 915 mm/year) and yielding values less consistent with the measured spring discharge.

What is more important than the difference in the estimation of effective infiltration by using the original and the modified APLIS method, is that the modified one provides a much more accurate spatial insight, allowing the delineation of preferential infiltration zones linked not only to surface karst features but also to fault damage zones. This can offer crucial guidance for groundwater protection strategies. By identifying areas of enhanced infiltration, this method not only supports a more precise recharge estimation but also highlights zones potentially more vulnerable to groundwater contamination. Such detailed spatial information, unavailable through traditional water balance approaches, can be instrumental in delineating protection zones for drinking water sources, especially in fractured and karst aquifers that are highly susceptible to rapid contaminant transport (White 2017; Medici and West 2021; Marín et al. 2021).

Eventually, one promising future development would be to use the modified APLIS method in a dynamic framework, by reapplying it on an annual basis, using updated climatic and geological observations if necessary. This would allow for a more responsive understanding of recharge variability under changing climatic conditions, rather than relying on long-term mean values (i.e., 2010–2022).

As a first check of the possibility of using the calibrated modified APLIS in conditions other than the annual average, the method was used, with the same parameters, to generate the Scirca spring annual discharge for the wettest and the dryest years (see the ***APLIS*** sub-section of the ***Results*** section). It was found that in the wettest year the APLIS output was quite close to the real discharge average (1247 vs. 1238 mm/year) and that in the dryest year was about 7% higher (783 vs. 736 mm/year). These results seem to be promising, particularly when considering that for using the modified APLIS on an annual basis rather than on a mean annual basis, a more accurate investigation should be done about the possible variations in water storage and on the lag-time between precipitation and discharge. These aspects are beyond the scope of the present work and they deserve further and more accurate analyses, also based on the study of recession curves and on the separation of base flow.

Indeed, transitioning from a static, average-condition model to a dynamic, year-by-year application of the APLIS method could reveal interannual variability in recharge behavior and further enhance its utility for proactive water management, especially in the context of climate-driven shifts in precipitation and snowmelt patterns. In this context, the integration of geo-structurally informed parametric methods like APLIS with traditional water budget models represents a forward-looking approach. It not only enhances recharge estimation but also fosters a more comprehensive groundwater management strategy, one that considers both environmental protection and resilience to future hydrological variability.

Eventually, by considering the key role that extensional tectonics play in the infiltration process, it is believed that, when faulted and fractured damaged zones are highly developed, the modified APLIS method could be effectively used even in fractured aquifers with poorly developed or no karst landforms.

Conclusions

The decision to employ a parametric method over a traditional approach for evaluating recharge in karst aquifers is frequently driven by the availability of thermo-pluviometric and territorial data. When both type of data are accessible for a specific area, it is beneficial to compare the results of both methods. This allows for cross-validation and assessment of the consistency and comparability of the outcomes, therefore indicating whether both approaches can be used and whether the assumptions made when using traditional methods, such as the choice of infiltration coefficients and soil storage capacity, are appropriate. Once the cross-check indicates that both approaches give reliable results in a certain area, as it seems to be the case of Northern Apennines, each of them can be indifferently chosen, in similar contexts, to estimate groundwater recharge and quantify groundwater resources.

In any case, when using both methods, a detailed reconstruction and characterization of spring recharge area and aquifer geometry, based on in situ geological and hydrogeological surveys, is needed, along with the estimation of mean precipitation at the appropriate time scale. In this respect, it must be underlined that the contribution of snow to total precipitation in mountains area is often difficult to quantify, as stations recording snow depth are randomly distributed and rain gauges able to quantify the snow are rarely used. Additional investigation about the contribution of snow to precipitation is needed to further decrease the uncertainty on the results of the two approaches, as precipitation is a key input parameter for both. Future research in the Apennines should prioritize the development of high-resolution, coupled snow-groundwater models, expanded ground-based monitoring networks, and targeted use of satellite data to capture the spatial and temporal variability of snowmelt-driven recharge. Such efforts are essential to improve water resource management under changing climatic conditions in this sensitive Mediterranean mountain environment.

Valuably, results suggest that the modified version of the APLIS method, which accounts for the contribution of fractures and fault zones to effective infiltration, could be conveniently used not only in limestone-karst areas, where karst landforms and fracture zones can be superimposed to each other, but also in any area where faulted and fractured damaged zones are highly developed, and strongly influence the infiltration process. This possibility might be investigated in the future.

The consistency between the recharge values derived from traditional water balance methods and the APLIS model reinforces their complementarity. While traditional approaches rely on climatic data, the parametric APLIS method captures the structural and geomorphic controls on infiltration, offering a more spatially resolved and structurally sensitive tool for groundwater resource assessment. Given its capacity to incorporate geological structures, soil types, and karst features, the APLIS method enhances the assessment of infiltration dynamics and thus serves as a valuable tool for both quantitative groundwater estimation and strategic water management planning. In fact, the infiltration map obtained by using APLIS makes it evident that looking ahead, a key improvement would be the dynamic application of the APLIS method on an annual basis, allowing recharge estimates to reflect interannual variability in precipitation, snowmelt, and evapotranspiration. This would support more adaptive and forward-looking groundwater management under evolving climate scenarios. The results obtained after a first check of the possibility of using the modified APLIS method on a time scale other than the mean annual are promising and indicate that it is worth developing further investigations, which could possibly take into account possible water storage variations. Altogether, integrating both traditional and parametric methods, particularly when applied with updated temporal resolution and structural awareness, represents a promising pathway toward more accurate, sustainable, and spatially informed groundwater resource management in complex karst environments.

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Authors' contributions All authors contributed to the study and manuscript. **D.F.:** conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review and editing. **C.C.:** conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review and editing. **A.M.:** data curation, formal analysis, investigation, methodology, software, visualization, writing – review and editing. **F.M.:** conceptualization, data curation, field work, geological sections elaboration, methodology, writing – review and editing. **I.S.L.:** conceptualization, methodology, writing – review and editing. **M.M.:** methodology, writing – review and editing. **A.T.:** conceptualization, methodology, writing – review and editing. **M.P.:** conceptualization, methodology, writing – review and editing. **D.V.:** data curation, investigation, methodology, supervision, writing – review and editing. All authors approved the final version of the article.

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Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Ethics approval and consent to participate Not relevant.

Consent for publication The manuscript is approved by all authors for publication. We declare that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

Competing interest No conflicts of interest exist in the submission of this manuscript.

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