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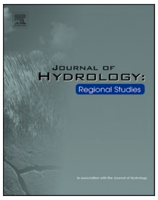

Recharge assessment of the Gran Sasso aquifer (Central Italy): Time-variable infiltration and influence of snow cover extension

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ABSTRACT

Study region: Carbonate karstified aquifers represent one of the most important groundwater reservoirs for both drinking purposes and environmental preservation. Currently, the recharge–discharge equilibrium in these aquifers is at risk of depletion from withdrawal increases and global change effects. Based on these factors, detailed analyses of recharge distribution over the last 20 years (2001–2020), both in terms of rainfall and snow melting contributions, have been carried out for the Gran Sasso regional aquifer (Central Italy).
Study focus: Using the same input data, water budgets at different time scales were calculated using the Turc, Thornthwaite and APLIS methods. In addition, simplified future scenarios considering the real risk of climate change effects have been implemented by applying an increase in temperature and a shortage of snow coverage periods.
New hydrological insights: The obtained aquifer recharge values are similar and a significant contribution to recharge from snowmelt has also been highlighted. The measured spring discharge values are higher with respect to the calculated recharge, especially in drought periods, underlining the resilience of groundwater resources in the Gran Sasso aquifer; these values are also confirmed by the different responses of spring discharge to recharge variations. A significant decrease in recharge and consequently in baseflow discharge is conceivable for future scenarios, revealing that immediate optimization measures are required to correct groundwater resources management and to avoid potential emergency conditions.

1. Introduction

Groundwater resources represent the main source of freshwater for human uses and for drinking purposes in particular (Chen, 2017; Hartmann et al., 2014), while at the same time, they play a fundamental role in maintaining a healthy environment, which includes surface water bodies and the biosphere as a whole (Hartmann et al., 2021; Martín-Arias et al., 2020). High permeability and significant storativity, coupled with relevant precipitation rates, are responsible for the consistent amount of renewable and long-term resources stored in aquifers (Bakalowicz, 2005; Kaufmann, 2016). Among hydrogeological systems, fractured and karstified carbonate rocks have a main role in hosting groundwater, both in terms of diffuse and concentrated infiltration and of spring discharge, with infiltration rates close to the precipitation amount, both in humid and arid conditions (Berthelin et al., 2020). Such karst aquifer

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outcrops cover more than 20% of European territory, and their springs supply water to several large cities and their citizens (Chen, 2017; Stevanović, 2019).

In addition, the European and Mediterranean karst aquifers are frequently concentrated in mountain ridges and peaks where they receive relevant to their elevation, the highest rate of precipitation, including snow contribution persistent on soil for several months.

All these characteristics, coupled with peculiar groundwater dual-flow (by karst conduits and by fracture network), increase the relevance for evaluating groundwater resource amounts, withdrawal management and effective recharge rates over time, in light of the effects of the normal seasonal and yearly variations of precipitation inputs (Hartmann et al., 2021). For all these reasons, fractured and karstified aquifers must be considered strategic to appropriately developing human society and maintaining environmental quality.

At the global level, but especially at the Mediterranean scale, the recharge/discharge equilibrium in groundwater systems, threatened by human withdrawals since at least the last century, is now under additional risk of depletion due to climate change, which undoubtedly modifies the recharge and discharge mechanisms, as demonstrated by several recent studies (Xanke and Liesch, 2022; Chen et al., 2018; Hartmann et al., 2014, 2017; Intergovernmental Panel on Climate Change, 2019; Kundzewicz et al., 2008). This is notably relevant for karst aquifers, which are particularly susceptible to climate change impacts (Taylor and Greene, 2008). Consequently, the balance between natural renewable resources and human needs for drinking and civil purposes has to be rediscussed and, where necessary, adapted to ensure the maintenance of appropriate water resource amounts and of ecosystem survival for future generations. This is necessary to achieve sustainable management of karst groundwater resources faced with reduced recharge and increased groundwater use. Therefore, water planners require improved and specifically adapted tools for the management of karst water resources.

Based on this framework, the KARMA project granted under the PRIMA call (Horizon 2020 programme) of the European Union (PRIMA, 2018) achieves substantial progress in the hydrogeological understanding and sustainable management of karst water resources across several scales (from hydrogeological basin to catchment of a single spring) to obtain valuable information, notably for stakeholders, on recharge, groundwater vulnerability and groundwater-dependent ecosystems for the entire Mediterranean area (Ollivier et al., 2020).

Our research group concentrated on Central Italy, where most groundwater resources are hosted by large fractured and partially karstified aquifers, reaching the extent of approximately one thousand of km^2, receiving rainfall amounts higher than 1000 mm/year with a mean infiltration of approximately 700 mm/year, and corresponding to the major ridges of the territory, which are frequently located at elevations higher than 2000 m asl. The paradigmatic example of such aquifers is the Gran Sasso Mountain, which includes the highest peak of Central Italy (approximately 3000 m asl) and the lowest latitude European glacier, known as Calderone (Grunewald and Scheithauer, 2010; Pecci et al., 2008; Tallini et al., 2013) and which is expected to disappear in a few years.

In this paper, we present the results of an updated water balance evaluation for the Gran Sasso aquifer and its springs, with the double aim: a) to distribute the recharge rate to small recharge areas instead of considering a mean value and to evaluate the infiltration distribution with altitude and snow cover and b) to verify the potential trend of recharge during the last twenty years. The obtained results have practical applications: on the one hand to provide updated information to drinking water companies and local authorities and to improve water management in order to optimize the use of available water resources at the aquifer scale, and on the other hand, to offer an example of possible impacts of climate change effects on groundwater resources, to be extended in similar contexts in Italy and at the Mediterranean scale.

2. Materials and methods

2.1. Hydrogeological setting

The Gran Sasso aquifer has been studied in detail over the last 25 years (Adinolfi Falcone et al., 2008, 2012; Amoruso et al., 2011, 2013, 2014; Barbieri et al., 2005; Boni et al., 1986; De Luca et al., 2016; Farroni et al., 1999; Ferracuti et al., 2006), and its mean infiltration rate has been evaluated to be approximately 700 mm/year. The Gran Sasso hydrostructure is defined as a calcareous-karstic aquifer system with a total extension of approximately 1000 km^2, and it can be considered the most representative karst aquifer of the central-southern Apennines (Fig. 1). At a glance, the Gran Sasso hydrogeological system as described in Amoruso et al. (2013) is characterised by Meso-Cenozoic carbonate units that host the aquifer, bounded along the northern side by terrigenous units (Miocene flysch) representing the regional aquiclude and along the southern side by Quaternary continental deposits (regional aquitard).

The Gran Sasso massif is characterized by the typical karst features of the Central Apennines, where active Plio-Quaternary tectonics have caused the recent filling of intramontane plains and river valleys by clastic and alluvial deposits (Cavinato and De Celles, 1999). The deposition of alluvial sediments precluded karst system evolution in the saturated zone, causing the development of mature karst features in recharge areas that are not reflected in discharge areas (Barbieri et al., 2005). At the massif core, an endorheic basin with a tectonic-karst origin, called Campo Imperatore (mean elevation 1650 m a.s.l.), acts as a preferential recharge area of the Gran Sasso aquifer and is fed by high rainfall and snowfall rates (Tallini et al., 2013).

The Gran Sasso karst aquifer hosts a unique regional-wide groundwater table with a mean hydraulic gradient of 5–20% (Amoruso et al., 2013). The aquifer has a total discharge ranging from 18 m^3/s to 25 m^3/s from its springs, including a highway tunnel drainage tapped for drinking water on both sides. The spring discharge, influenced by the recharge rate, is showing during last five years some lowering testified by the drinking supply companies tapping the springs.

The peculiarity of the Gran Sasso aquifer is also due to the high percentage of spring withdrawals for drinking purposes and its position inside the Gran Sasso and Laga Mts. National Park, testifying to the dual need of providing for the human population without

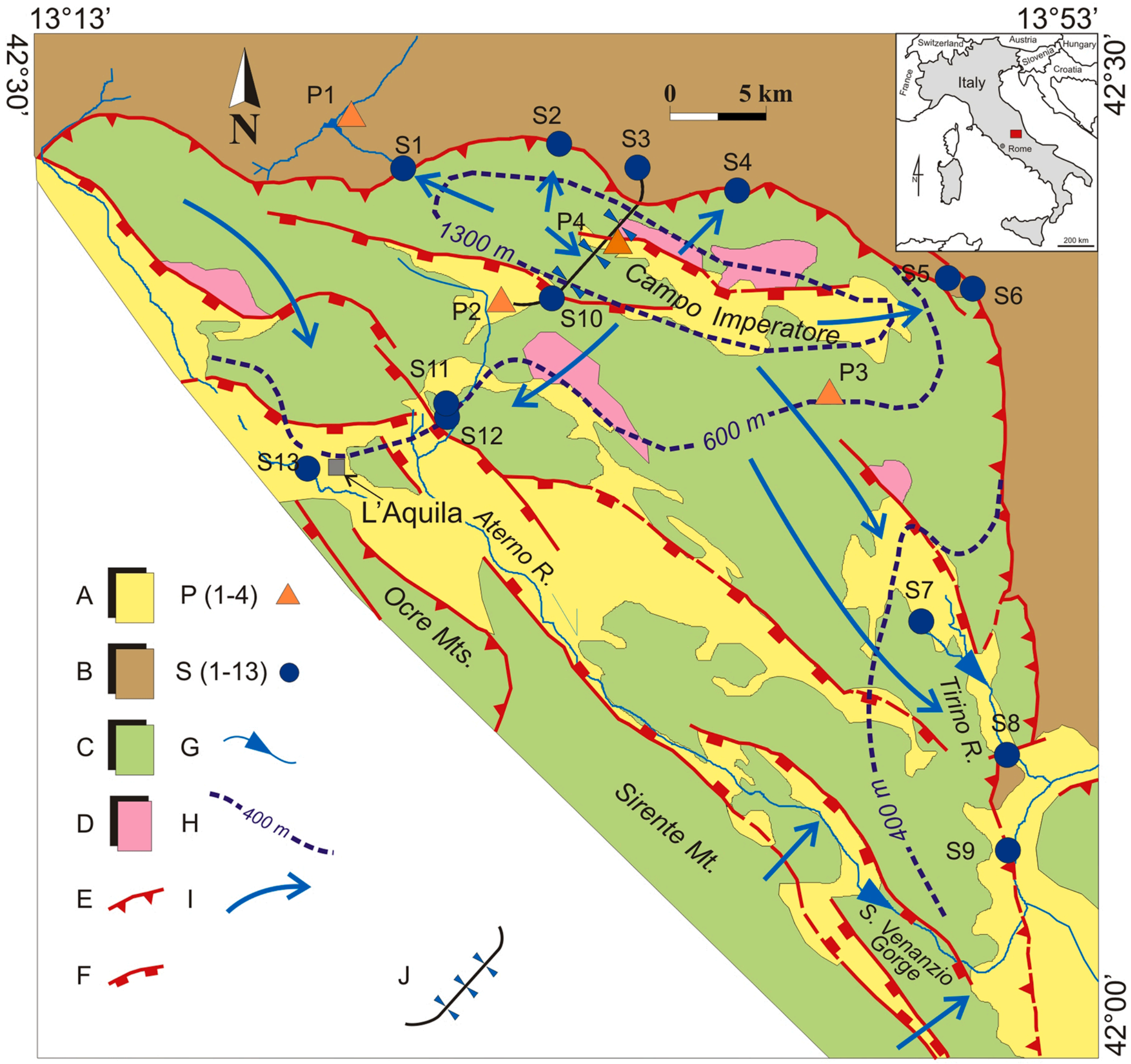

Fig. 1. Simplified hydrogeological setting of the Gran Sasso aquifer. A Aquitard (continental detrital units of intramontane basins, Quaternary), B aquiclude (terrigenous turbidites, Mio-Pliocene), C aquifer (calcareous sequences, Meso-Cenozoic), D low permeability bedrock (dolomite, upper Triassic), E main thrust, F main extensional fault, P(1-4) selected climatic gauges, S(1-13) main springs, G streambed spring, H presumed water table elevation (m a.s.l.), I regional groundwater flowpath, J highway tunnel drainage
(modified from Petitta et al., 2015).

compromising the environment and the ecosystems. However, the very distinctive characteristic of the Gran Sasso aquifer is its groundwater drainage by two parallel tunnels drilled approximately 50 years ago to realize a highway, which intercepts approximately 1.5 m^3/s of groundwater close to 1000 m asl, modifying the natural setting of the aquifer and inducing the discharge reduction of some springs (Adinolfi Falcone et al., 2008; Amoruso et al., 2013; Celico et al., 2005). The tunnels are still active and represent an unusual potential source of contamination to groundwater because they are tapped immediately beneath the road by lateral drainages at the aquifer core; this unique interference is compounded by the presence within the highway tunnels of the noteworthy Underground Laboratories of the Nuclear Physics National Institute. These conditions cause the temporary suspension of the European rule for Drinking Water Safeguard Zones (European Commission 2000, 2007) in tapping tunnel drainages. Throughout the aquifer, approximately 25% of its renewable resources are tapped for drinking purposes, mainly from springs (including highway tunnel drainage) and limited by well withdrawals.

2.2. Water balance calculation and parameter estimation

The evaluation of the Gran Sasso rainfall has been carried out by considering two annual gradients for the northern and southern slopes of the massif (Scozzafava and Tallini, 2001). The gradients were calculated by linear correlation of altitude and climatic parameter data (rainfall, temperature, snow) acquired by 21 Gran Sasso thermorain gauges over a period of 20 years (2001–2020). The Campotosto and Assergi gauges (respectively P1 and P2 in Fig. 1, Table 1) have been considered as reference data for both northern and southern slopes. The gradients were then applied from the selected gauges, identifying rainfall distribution values over the entire aquifer for each year. In addition, the "average" rainfall values were derived from data from the entire monitoring period (2001–2020).

By applying the two calculated gradients, annual maps of rainfall distribution and isohyets were created from 2001 to 2020 and for the "average year" (Fig. 2a) using ArcGis 10.3 software with a 100 × 100 m pixel raster. The adopted reference system of coordinates is WGS 1984 UTM Zone 33 N. The analysed area extends approximately 1034 km^2. The elevation map was derived by the digital elevation model (DEM) (Fig. 2b).

An estimation of the temperature gradient and the related isotherm maps have also been computed by linear correlation among all existing gauges, and applying the obtained gradient with respect to the Castel del Monte gauge, selected as reference starting point (P3 in Fig. 1, Table 1).

Through the analysis of data, the net infiltration and consequently the Gran Sasso water budget were computed using three different approaches, the Turc (1954), Thornthwaite (Thornthwaite and Mather, 1957), and APLIS (Andreo et al., 2008) methods, to verify the reliability of the three methods for recharge assessment.

The Turc method (TUR) for the estimation of real evapotranspiration (ETR) at the yearly scale (Turc, 1954) has been applied to assess the net inflow values.

The effective infiltration of the Gran Sasso aquifer has also been calculated at the monthly scale for the solar year starting in January by applying the Thornthwaite method (THR) and modified to discriminate between runoff and net infiltration by applying the soil curve numbers (Dilshad and Peel, 1994) for different recharge areas inside the aquifer. The maximum water storage in the soil, adopted as the field capacity value, has been associated with each curve number, as described by Scozzafava and Tallini (2001). By this method, the role of unsaturated soil in influencing the ETR has also been considered; it is noteworthy that most of the recharge area has negligible or very limited soil thickness due to direct rock outcrops, which frequently occur in karst regions.

The modified Thornthwaite method has been applied to obtain the different parameters useful to determine the infiltration value (such as ETP, ETR, and field capacity) and to assess the monthly water budget. Consequently, the annual rainfall gradient (*Ga)* calculated as previously discussed, has been considered as a starting point to derive the monthly rainfall gradients (*Gm)* by (1):

$$Gm_i = \frac{Rm_i}{Ra_i} Ga \tag{1}$$

where $i = 1., 12$ (month), Gm is the unknown variable, Rm is the monthly rainfall, and Ra is the annual rainfall (Scozzafava and Tallini, 2001). In other words, monthly rainfall gradients have been obtained considering the ratio between monthly rainfall and total rainfall of each gauge. Both the above-described methods are based on the hydrological budget equation, expressed by incoming and outgoing volumes (2):

$$\mathrm{I = P - ETR\text{-} R} \tag{2}$$

The runoff parameter (R), according to Scozzafava and Tallini (2001), has been considered to be approximately 0.3% of the total rainfall. The negligible role of runoff in carbonate fractured and karstified aquifers of Central Italy has been well known and consolidated for a long time (Boni et al., 1986).

In addition to the described methodologies based on climatic parameters, the APLIS method (APR) has been applied to directly estimate the mean annual recharge of carbonate aquifers, expressed as a percentage of precipitation (Andreo et al., 2008). A combination of geological, geographic and morphologic variables, such as altitude (A), slope (P), lithology (L), infiltration landforms (I), soil types (S) and a correction factor (Fh) dependent on hydrogeologic behaviour, is used for the evaluation, in addition to input parameters such as average annual rainfall and its spatial distribution (see Fig. 2a). To obtain a map of the average recharge rate, available information is transformed into dimensionless values from 1 to 10 by a ranking system and subsequently used in the following Eq. (3):

$$R = [(A + P + 3x\,L + 2x\,I + S)/0{,}9] *Fh \tag{3}$$

where the weight of each parameter is intended to represent its relevance to the recharge rate. The lithology (L) has a triple influence as those of altitude (A), slope (P), and soil type (S), while areas of preferential infiltration (I) are twice as important. The obtained annual recharge rate was grouped into five recharge classes. In addition, APR allows us to obtain maps of the spatial distribution of recharge by the superimposition of the following GIS information layers: slope DEM map in Fig. 2b, based on a 20 × 20 m cell and a lithological/hydrogeological map. Different scores have been assigned to each lithology based mainly on their fracturing and karstification. The lithology score ranges from 10 to 2, assigned to the aquifer and to the aquiclude, respectively. Even the area of Campo Imperatore,

Table 1
Climatic gauges selected as representatives for rainfall, temperature and snow parameters.

Id	*Name*	*Altitude [m a.s.l.]*	*Type of data*	*Period*	*Slope*	*Mean annual value*
P1	Campotosto	1344	Rain	2001–2020	Northern	1240 mm
P2	Assergi	991	Rain	2001–2020	Southern	850 mm
P3	Castel Del Monte	1346	Temperature	2001–2020	Southern	8.9 °C
P4	Campo Imperatore	2137	Snow	2010–2020	Southern	51.8 cm

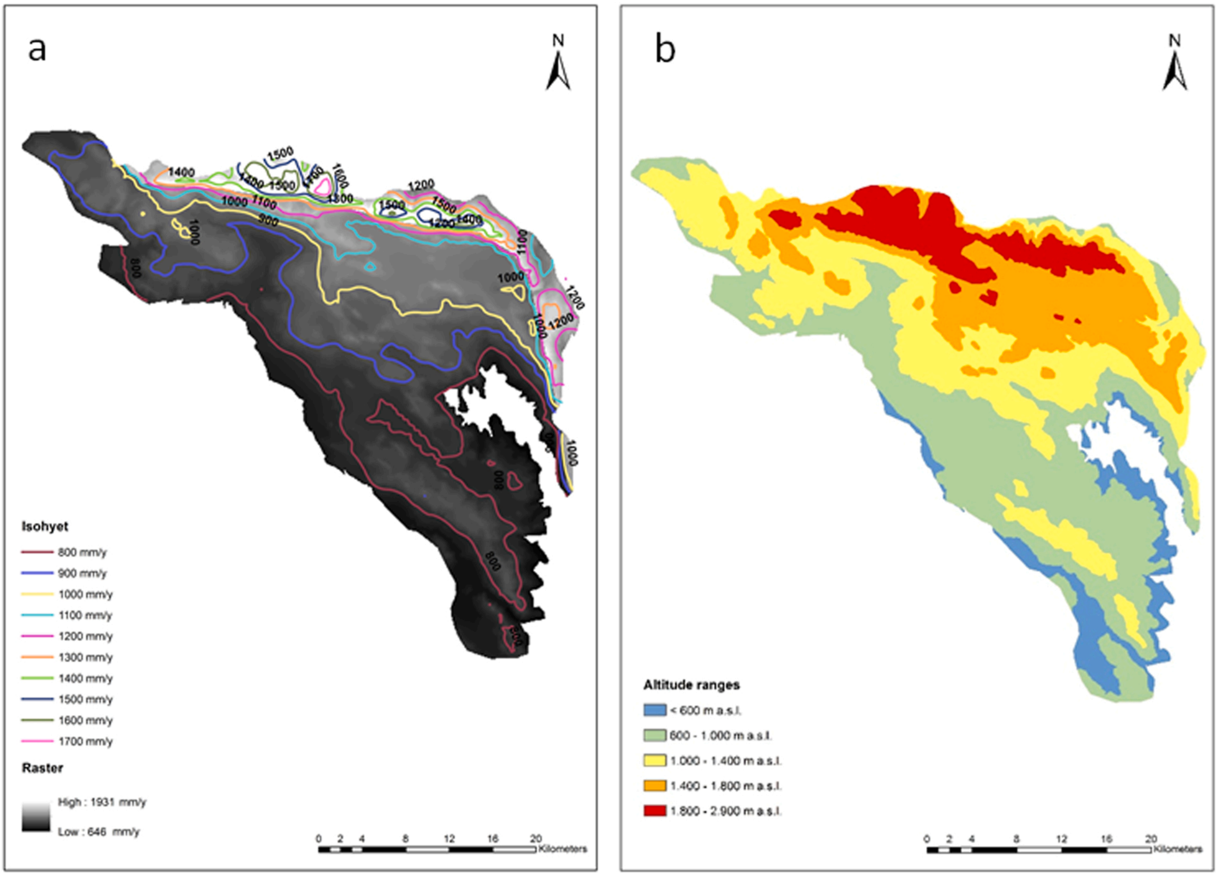

Fig. 2. Rainfall (a) and elevation (b) distribution maps of the Gran Sasso aquifer.

defined as a preferential recharge area, has been identified with the maximum score. Areas of preferential infiltration were downloaded from the geomorphological map of PAI, a regional management tool (https://autoritabacini.regione.abruzzo.it/index.php/carta-geomorfologica-pai). The soil map was derived from the geoportal of the Abruzzo region. The main geometric reference from which the land use limits were taken was represented by the 1997 AIMA digital orthophoto (scale 1:10000) and Landsat TM5 satellite images (30 ×30 m pixels). The last calculated parameter is the recharge correction factor Fh, which depends on the hydrogeological characteristics of the rock outcrops and is expressed as a percentage of precipitation. A combinatory procedure has been applied to produce a single calculation algorithm that enables the determination of the recharge percentage resulting from APR application among 100 × 100 m rasters for the whole domain. The isohyet map (Fig. 2a) has been overlapped with the Aplis map to obtain the infiltration and recharge rate of the aquifer.

The Gran Sasso aquifer water budget and recharge rate depend not only on rainfall but also on seasonal snow cover and related snowmelt contributions to infiltration (Fazzini and Bisci, 1999). To calculate the snowmelt fraction, a monthly gradient was applied through a linear correlation between the altitude and the monthly snowfall sum for the 1960–1990 period, where available (P1 and P4 in Fig. 1 and Table 1). In other words, a literature snow gradient (Fazzini and Bisci, 1999) has been applied considering the real data measured at the two reference stations (P1 and P4) and consequently deriving the snow thickness value at higher and lower elevations. By this way, a snow coverage function of the elevation has been obtained for each snowing month (November to April), with related snow thickness increasing with elevation. The obtained monthly gradients were then used to identify the fraction of recharge due to snow for the 2010–2020 period, when snow data from Campo Imperatore (P4 in Fig. 1 and Table 1) were available. In this case, snow evaluation was based on the hydrological year starting since November until April of the following solar year. Due to the absence of real snowfall data for the 2001–2009 period, the snowmelt contribution was estimated for this period as 15% of the recharge, applying a precautionary rate with respect to the 20% obtained from real data during the 2010–20 period. This additional recharge contribution has been applied to the infiltration calculated by all three methods (TUR, ETR; APR) for each observation year and on average, equally spreading the snow recharge during the three snow melting months of March, April and May.

2.3. Main spring discharge data analyses

To compare the water balance calculated through the different methods and to evaluate the springs' response to aquifer recharge variations, discharge data for the main springs have been collected and analysed. Discharge data for the monitoring period

Table 2
Mean discharge values (2001–20) of the selected main springs (see Fig. 1 for location).

ID	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
Spring	Chiarino	Rio Arno	Northern Drainage	Ruzzo	Vitella d'Oro	Mortaio d'Angri	Capodacqua Presciano	Basso Tirino	San Calisto	Southern Drainage	Tempera	Vera	Vetoio - Boschetto
Altitude m a.s.l.	1330	1524	964	990	650	660	340	300	300	966	650	650	630
Mean discharge m^3/s	0.4	0.2	1.1	0.8	0.7	0.3	5.8	6.7	1.4	0.5	1.2	0.3	1

(2001–2020) have been provided mostly by water suppliers and the Regional Environmental Agency and then coupled with data obtained during previous research projects (Adinolfi Falcone et al., 2012; Amoruso et al., 2011). Information on spring discharge has been collected at different time scales (from hourly to seasonal scales) depending on the purposes of monitoring. Most of the spring data are unfortunately not continuous for the analysed period; missing information has been derived starting from the known discharge measures and estimated as the average of the available data. In case of missing discharge data for the whole year, the spring discharge has been assumed from the correlation line equation obtained comparing real known spring discharge with the expected discharge obtained from the TUR water balance calculation; by this way, a reasonable discharge value has been assigned to the years with missing data of single springs. The acquired data were checked and validated. The real mean discharges calculated for the 2001–2020 period for each spring are summarized in Table 2 and consider each observation solar year.

3. Results

The calculated gradients of both rainfall and temperature have been applied to the whole domain. The computed annual rainfall gradients are 30 mm/100 m for the southern slope and 42 mm/100 m for the northern slope. The obtained temperature gradient was − 0.59 °C/100 m. The benchmark for snow monitoring was the Campo Imperatore gauge (S4 in Fig. 1 and Table 1), and the applied monthly gradients corresponded to 3.8 cm/100 m for November, 4.2 cm/100 m for December, 6.7 cm/100 m for January, 3.3 cm/100 m for February, 2.4 cm/100 m for March and 4.9 cm/100 m in April. Consequently, snow coverage on the aquifer and its thickness have been obtained in each 100 × 100 cell for the entire period with real data (2010–2020). The snow fall has been converted in equivalent mm of rain (1 cm of snow = 1 mm of rain).

Considering a negligible contribution to runoff (0.3% of total rainfall), the net infiltration was calculated using the three previously mentioned methods. Details are included in the Supplementary File (Tables S1-S3).

3.1. *Turc method (TUR)*

The average annual recharge calculated over the 20-year period using the Turc method (TUR) is 19.9 m^3/s, including a contribution due to snowmelt of 3.2 m^3/s. The average ETR value is approximately 444 mm/y, while the average infiltration value from rainfall corresponds to 508 mm/y, which is integrated with 98 mm/y due to snowmelt. The year 2007 shows the lowest recharge of

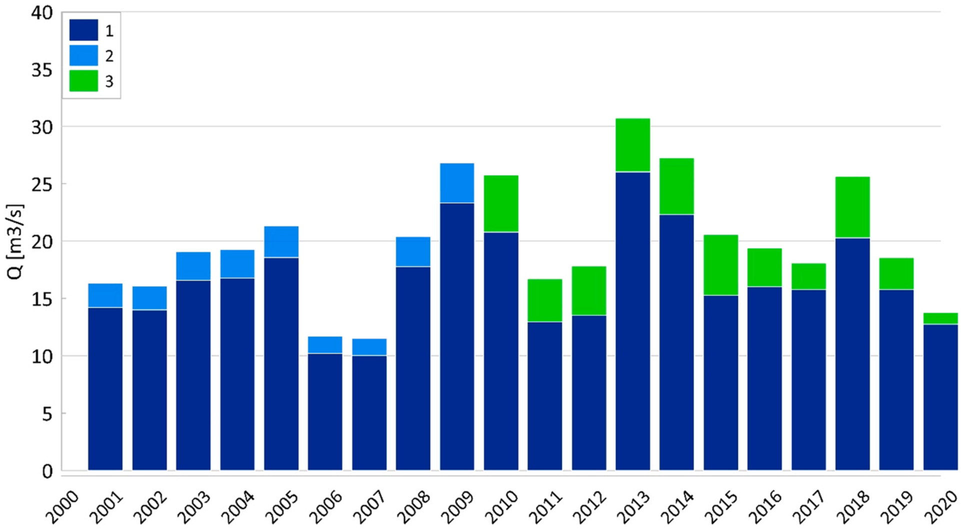

Fig. 3. Yearly recharge results by TUR application: 1) recharge from rainfall; 2) estimated snow contribution (15% of recharge); 3) calculated snow contribution.

11.5 m^3/s (10 m^3/s from rainfall and 1.5 m^3/s from snowmelt), while 2013 has the highest recharge of 30.7 m^3/s (26 m^3/s from rainfall and 4.7 m^3/s from snowmelt). Fig. 3 shows the calculated recharge, including the snowmelt component, differently calculated for 2001–2009 (15% of recharge) and 2010–2020 (from real data).

3.2. *Thornthwaite method (THR)*

Using the Thornthwaite method (THR), the calculated average annual recharge results in approximately 18.5 m^3/s, including a contribution from snowmelt of 3.2 m^3/s. The average value of ETR is approximately 491 mm/y, while the corresponding infiltration value is 558 mm/y. 2006 was the driest year (with a recharge of 9.8 m^3/s, of which 8.5 m^3/s was from rainfall and 1.3 m^3/s was from snowmelt), while 2013 had the highest recharge of 27.2 m^3/s (22.6 m^3/s was from rainfall and 4.7 m^3/s was from snowmelt). The main results are summarized in Fig. 4.

3.3. *APLIS method (APR)*

Through the APLIS method (APR), the Gran Sasso aquifer recharge rates are predominantly moderate, with an effective infiltration percentage of 51.6% of the total rainfall. The Gran Sasso massif, according to APR, is characterized by a preferential recharge area, the Campo Imperatore basin, with an infiltration rate of 76.7% (Fig. 5). The concentrated infiltration phenomena are due to the combination of different relevant parameters, such as the carbonate complex outcrop, fracture density, scarce vegetation cover and limited soil thickness. However, in limited areas near the boundaries, the presence of low-permeability deposits reduces recharge to low (20–40%) and very low (<20%) levels (Fig. 5). Allogenic contributions are considered negligible, according with a very limited contribution by runoff (0.3% of total rainfall).

The aquifer recharge through direct infiltration was calculated by overlaying the obtained recharge rate map with the rainfall map obtained for each year. The average recharge rate is 19.4 m^3/s (3.2 m^3/s from snowmelt and 16.2 m^3/s from rainfall), and the equivalent average infiltration value is 594 mm/y (496 mm/y from rainfall and 98 mm/y from snowmelt).

For TUR, 2007 is characterized by a minimum recharge rate of 13.7 m^3/s (11.9 m^3/s from rainfall and 1.8 m^3/s from snowmelt), while for TUR and THR, 2013 is characterized by the highest recharge rate of 21.3 m^3/s, including recharge due to snowmelt of 4.7 m^3/s (Fig. 6).

3.4. *Main spring discharge data*

To verify the consistency of the estimated recharge values, a comparison with the discharge data of the main springs (Fig. 1 and Table 2) of the same 2000–2020 period was carried out.

The Capo Pescara spring, the largest spring located in the south-eastern corner of the aquifer, has not been included because it is fed by both the Sirente and Gran Sasso aquifers, with a prevailing contribution from the Sirente aquifer (Scozzafava and Tallini, 2001; Petitta and Tallini, 2002). As shown in Fig. 1, a groundwater seepage from the Sirente aquifer towards the Capo Pescara spring (S9) is certified. Recent studies (Stoch et al., 2016) suggest that Capo Pescara discharge is fed prominently from the Sirente Aquifer, with a minority contribution from Gran Sasso aquifer: Due to the impossibility to quantitatively assess the Gran Sasso aliquot of the discharge, its contribution to the water budget has been neglected, accepting an underestimation of the total discharge of the Gran Sasso aquifer.

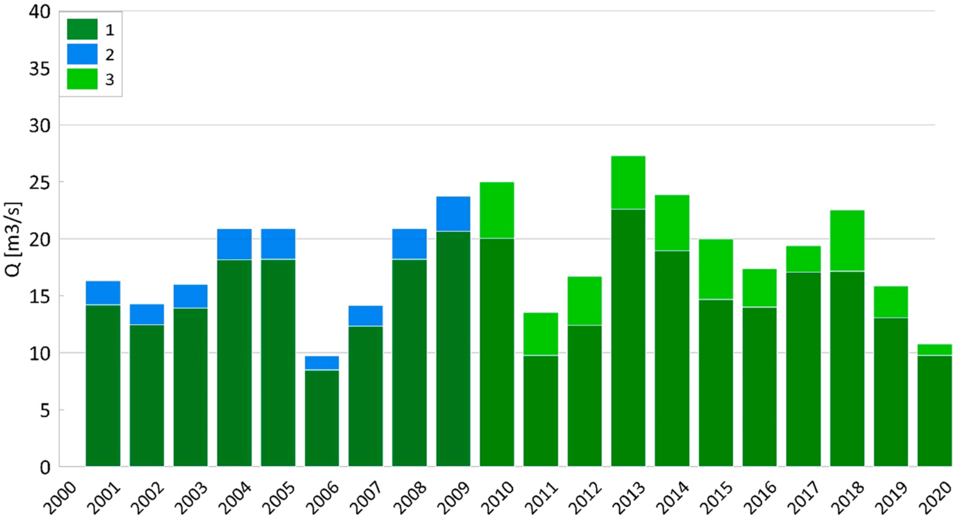

Fig. 4. Yearly recharge results by THR application: 1) recharge from rainfall; 2) estimated snow contribution (15% of recharge); 3) calculated snow contribution.

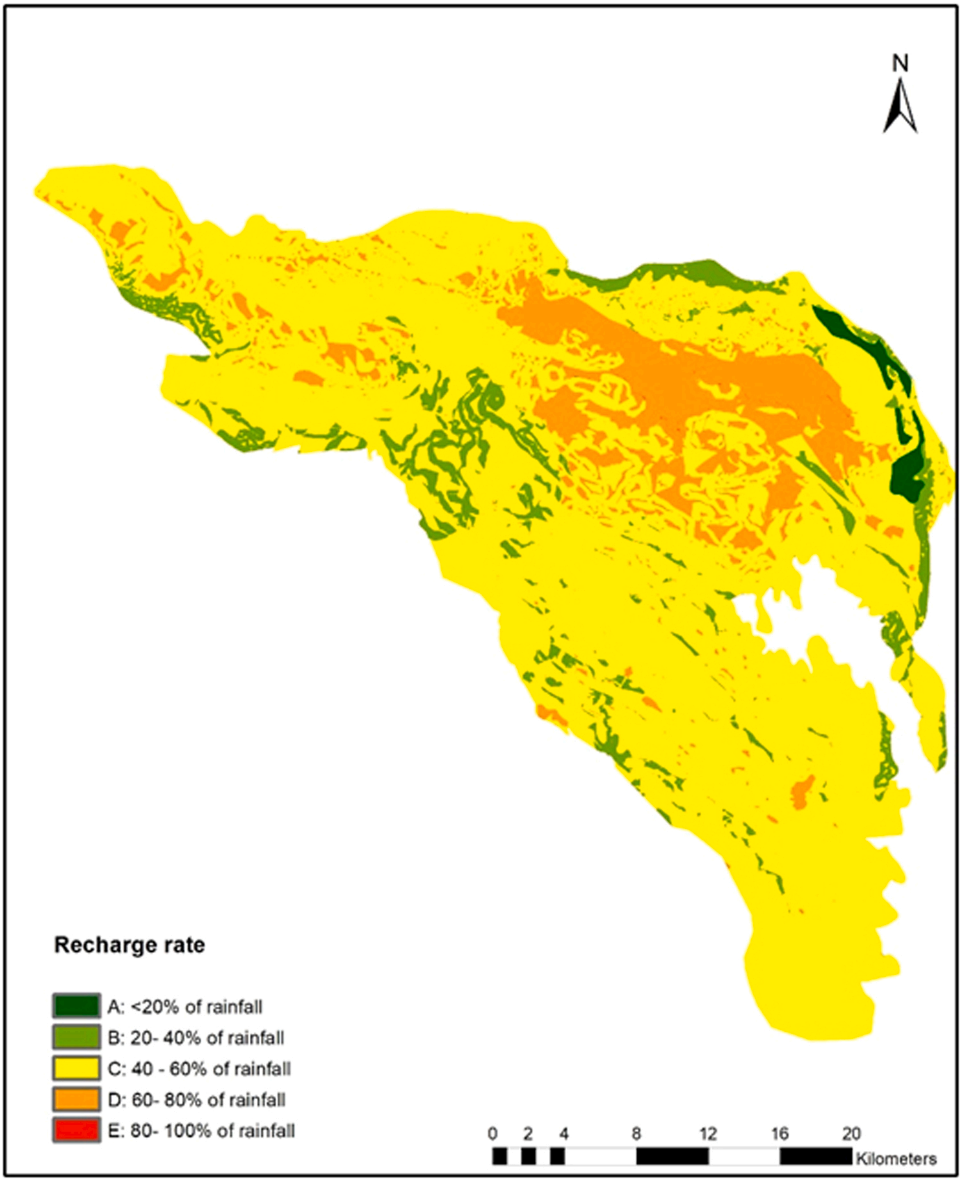

Fig. 5. Recharge rate map obtained by APR: letters refer to 5 infiltration rate classes.

The total long-term mean discharge of the aquifer corresponds to 20.4 m^3/s. The springs of the Tirino Valley (S7 and S8, including minor streambed springs) are characterized by a consistent and constant discharge over time, accounting for approximately 60% of the total Gran Sasso spring discharge.

4. Discussion

4.1. Recharge evaluation comparison

The reliability and representativity of the different applied methodologies can be assessed by comparing the results obtained through the three approaches, both in terms of recharge values and their distribution in the study area.

The analysis was conducted on both rainfall recharge values and total recharge (rainfall + snowmelt) results. The calculated mean rainfall recharge and related standard deviation (SD) are 16.7 ± 4.2 m^3/s for TUR, 15.3 ± 3.9 m^3/s for THR and 16.2 ± 2.4 m^3/s for APR, showing a difference among mean values lower than calculated standard deviations (< 1.5 m^3/s). In addition, for TUR and APR, ± 1 SD includes 75% of the calculated values, while for THR, it includes 70% of the values, highlighting the adequate representativity and accuracy of the adopted methods. The same analysis, carried out on total recharge values (rainfall + snowmelt) for the 2010–2020

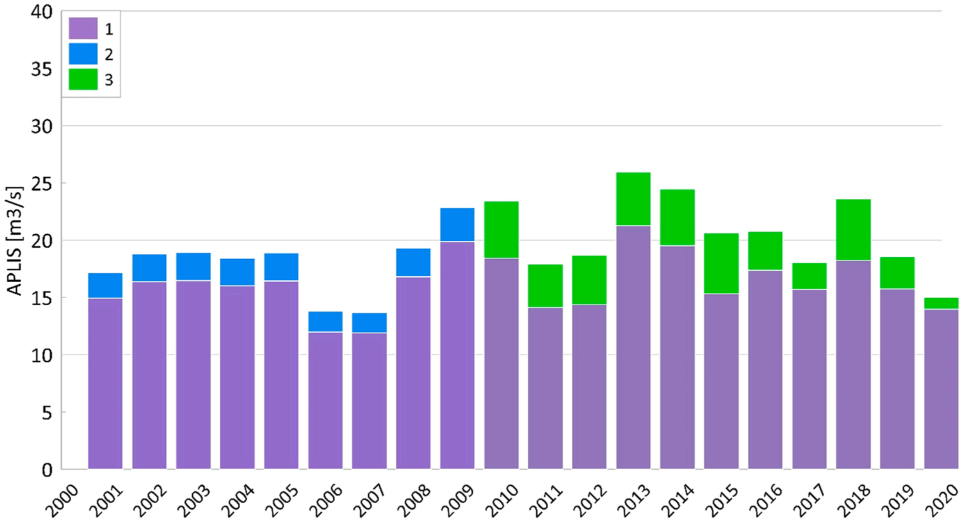

Fig. 6. Yearly recharge results by APR application: 1) recharge from rainfall; 2) estimated snow contribution (15% of recharge); 3) calculated snow contribution.

period, shows mean ± SD values of 21.3 ± 5.2 m^3/s, 19.3 ± 5.1 m^3/s and 20.6 ± 3.4 m^3/s for TUR, THR and APR, respectively. Differences among mean values are confirmed to be lower than calculated standard deviations, and the mean ± 1 SD includes 73% of obtained results for TUR and APR and 64% for THR. The comparability of the adopted approaches has been tested by matching results among different methods. In detail, the comparison between rainfall recharge values shows an R^2 of 0.74 comparing THR and APR, and an R^2 of 0.83 comparing THR and TUR, while the TUR-APR correlation line indicates the highest R^2 of 0.94, probably due to the same annual scale basis. Looking at total recharge values (2010–2020 monitoring period), the obtained R^2 values are 0.92 between TUR and THR, 0.97 between TUR and APR and 0.89 between THR and APR. The increase in correlation considering the total recharge, including the snow effect, supports the hypothesis of significant contributions from snow to recharge. At the same time, the correlation increase also indirectly testifies to the representativity of the approach adopted for snow recharge estimation.

By all methods, a higher recharge value was recorded in 2013, while the driest years were recognized in the two-year periods 2006–07 and 2011–12. In addition, a common decreasing trend in recharge values has been identified from 2014 to 2020, with the only exception recorded in 2018, where measured rainfall values were higher, as in other areas of Central Italy (Lancia et al., 2020; Sappa et al., 2019).

The analyses of the values obtained through APR highlight that recharge distribution is strongly dependent on the elevation belt, despite lithology and infiltration landforms having weights of 3 and 2, respectively, in the Aplis formula. The medium-low altitude belts, unlike the TUR and THR results, seem to be strongly influenced by recharge variations, especially in drought years. Conversely, the high-altitude belts guarantee, even with different weights, the highest recharge rates, confirming the results of the TUR and THR recharge distribution analyses.

The role of high elevation areas in aquifer recharge processes becomes even more important considering the influence of snow coverage and consequent melting. As mentioned in the previous paragraphs, the contribution of snow melting to the water balance has been calculated using real data only for recent years (2010–2020), when it was found that 60% of snow recharge comes from altitudes higher than 1400 m a.s.l., while the remaining 40% arrives from elevations ranging between 600 m and 1400 m a.s.l.

4.2. *Total spring discharge and computed recharge analysis*

To verify the reliability of the recharge values obtained with the application of different methods, the real total spring discharge (TSD) and the recharge values gathered from the three methods (TUR, THR, APR) were compared. To assess TSD, all major springs were considered (see Fig. 1 and paragraph 3.4), covering close to 100% of the total aquifer discharge. Fig. 7 shows the comparison between the annual values of recharge obtained by the three applied methods and the measured discharge of the aquifer. In principle, recharge represents the annual renewable resources in an aquifer, while discharge is expected to fit only partially with recharge values due to the storage parameter in the hydrological budget. Nevertheless, karst aquifers usually show a fast response to recharge inputs, and consequently, for this case study, a high correlation between recharge and discharge values at the annual scale is expected.

In fact, TUR and TSD values are well correlated (R^2 =0.86) (Fig. 7L), showing a slight overestimation of TUR with respect to TSD for the rainy years (when TUR > 22.5 m^3/s) and a slight underestimation for drought years. A similar match (R^2 =0.85) was obtained by TSD and recharge calculated with THR (Fig. 7C). In this case, a general underestimation of THR with respect to TSD was observed, which was more evident in the driest years. The comparison between APR and TSD shows the best alignment with respect to the X═Y line (Fig. 7R) but with a lower correlation (R^2 =0.81), confirming a slight underestimation trend of APR with respect to TSD. The three comparisons in Fig. 7 highlight that aquifer discharge is higher than the calculated stored recharge of the same year. The reason for this

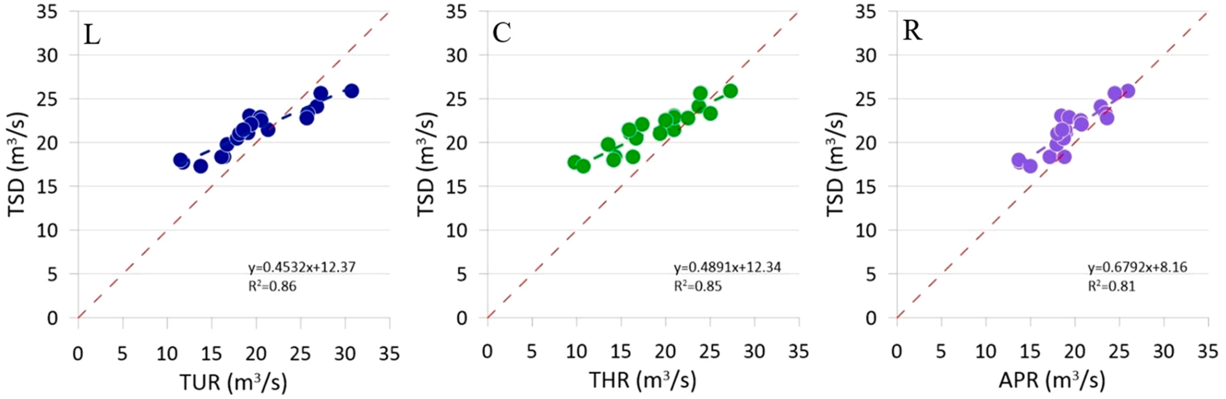

Fig. 7. Correlation between the yearly recharge calculated in the three different methods (TUR, THR and APR) and the discharge of the springs (TSD) considered for each observation year.

finding can be attributed to different causes:

- An underestimation of aquifer recharge due to the adopted procedure for rainfall and snow contributions could be one cause; we cannot exclude this possibility, but this condition is more clearly evident for years with a low recharge rate, and the applied methods for recharge assessment are the same for all years.
- An overestimation of aquifer discharge due to input to springs from different hydrogeological basins could be another cause; we exclude this possibility due to several studies based on hydrochemistry and isotope data, indicating that no external recharge areas can affect the Gran Sasso spring discharge;
- A third possibility, the most reliable in our opinion, is the so-called "memory effect", which is able to modulate the response of the springs to meteoric recharge (Fiorillo and Doglioni, 2010), frequently occurring in regional karst aquifers; in other words, during years having a limited recharge rate, the spring discharge is sustained not only by the corresponding recharge input, which is directly connected with the karst system, but also by a significant and persistent base-flow, which is due to the circulation in the secondary fracture network and matrix porosity, enhancing the role of the aquifer storage capacity. This memory effect would be more evident including in the TSD the contribution from Capo Pescara spring (S9) we initially discarded.

Going deeper into the recharge–discharge comparison process, the annual mean discharge referred to each of the considered main springs belonging to the Gran Sasso aquifer has been compared with the total recharge calculated with TUR. The analyses of the trend over time of TUR and single spring discharge allowed classification into three groups depending on the observed correlation. Specifically, the five main springs show a significant correlation with respect to TUR ($R^2 > 0.45$); three are characterized by a limited match with an R^2 ranging between 0.25 and 0.45, while five seem to be unrelated to recharge variation ($R^2 < 0.25$). As stated in Section 2.3, the strong heterogeneity in real spring discharge available data, sometimes incomplete for the considered period, surely affects the obtained correlation values.

In addition, the analyses of annual recharge–discharge correlation clearly highlight the different responses of springs, pointing out immediate or time-delayed responses with respect to computed recharge variations at the annual scale.

The discharge of springs located on the northern side of the Gran Sasso massif (S1 to S6 in Fig. 1) shows a fast response to annual recharge variations (TUR). A clear example is represented by the Rio Arno spring (S2 in Fig. 1), fed by the top level of the aquifer (Tallini et al., 2014). In fact, as shown in Fig. 8, the annual Rio Arno spring discharge (blue dots) follows the variation observed for TUR (orange bars); years characterized by high recharge rates are reflected on high spring discharge values and vice versa, as confirmed by an R^2 of 0.54.

In contrast, springs monitored on the southern side (S7-S13 in Fig. 1) reflect the variation in aquifer recharge with some delay. In fact, the southern drainage discharge of the highway tunnel (S10 in Fig. 1) seems to follow the effect of the variations in aquifer recharge with a year delay (Fig. 9a), reflecting the effect of a rainy or dry year by an increase or decrease in annual discharge one year later. Consequently, in comparing TUR and discharge data, the R^2 significantly increases from a value of 0.30 to a value of 0.56, applying spring discharge values to the previous year calculated recharge. The delay is more evident at the Tirino River (S9 in Fig. 1), whereby the annual TUR value shows its effects with approximately a two year delay (Fig. 9b). The comparison between spring discharge and TUR highlights that no correlation ($R^2 = 0.01$) is obtained comparing data without applying any delay in spring response, while R^2 increases to 0.44 when comparing discharge values to recharge from two years prior.

These results are consistent with the conceptual regional model of groundwater flow (Petitta and Tallini, 2002; Tallini et al., 2013, 2014), where Tirino River springs (S9 in Fig. 1) are supplied by the regional aquifer and are characterized by a steady-state regime. Considering the hydrogeological features of this spring, the observed delay recorded in its disdose–response to variations in aquifer recharge is in agreement with the hypothesis, as mentioned above, of the "memory effect". The memory effect is widely used to assess the response of groundwater in karst systems (Massei et al., 2006; Mayaud et al., 2019; Meeks and Hunkeler, 2015; Delbart et al., 2016;

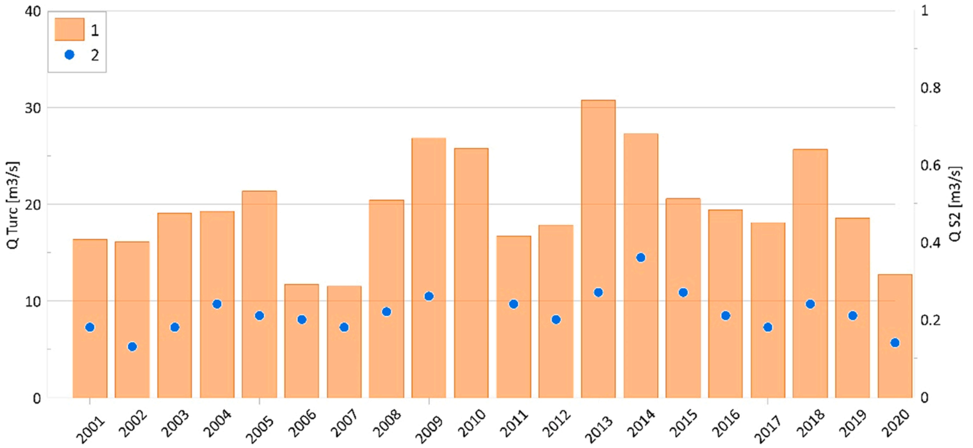

Fig. 8. Comparison over time between calculated recharge with TUR (1) and S2 (in Fig. 1) spring discharge (2); missing dots (2010) correspond to unavailable data periods.

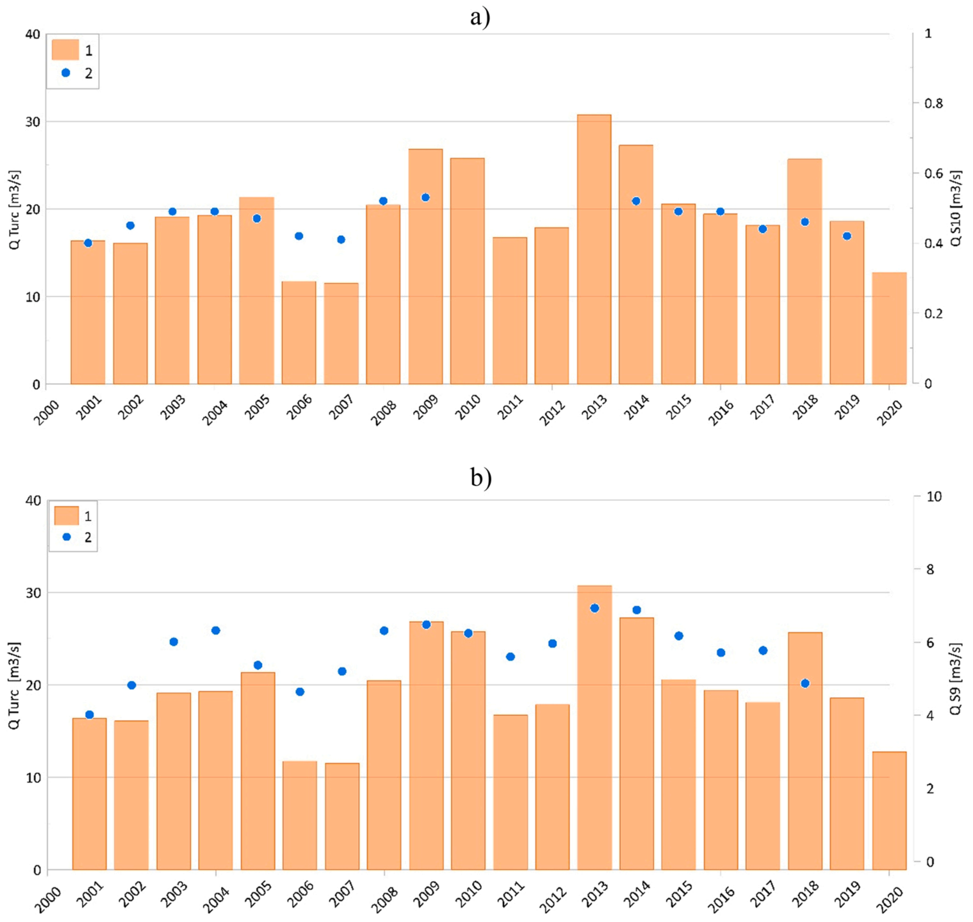

Fig. 9. Comparison over time between calculated recharge with TUR (1) and discharge (2): a) one-year shifted S10 discharge and b) two-year shifted S9 discharge; missing dots mean not available data period.

Schuler et al., 2020); it is related to the storage capacity of an aquifer (Chiaudani et al., 2019; Fiorillo et al., 2015; Garfias-Soliz et al., 2010) and is particularly high in systems in which the base flow component is prevalent (Pulido-Bosch et al., 1995), as for the Tirino River spring (Fig. 9b).

4.3. Observed decrease in recharge and possible simplified future scenarios

The results obtained from the calculated water budget of the last 20 years (2001–2020) show an average recharge of 606 mm/y for TUR, 558 mm/y for THR and 594 mm/y for APR, including approximately 17% due to the contribution of snowmelt. Previous studies have also estimated the average net infiltration feeding the Gran Sasso aquifer using both direct (Boni et al., 1986) and indirect methods (Scozzafava and Tallini, 2001). Boni et al. (1986) estimated an effective infiltration of approximately 700 mm/y, assuming that the annual spring discharge is equivalent to aquifer recharge. In contrast, the values obtained by Scozzafava and Tallini (2001) using the modified Thornthwaite method estimated a recharge value of 506 mm/y, representing approximately 53% of the average annual rainfall (945 mm/y); snow contribution is not included in their budget analysis.

In our study, the long-term (2000–2020) calculated average recharge on monthly basis (THR) corresponds to 462 mm/y, which is approximately 48% of the average annual rainfall (955 mm/y). Considering the comparable values of rainfall recorded in the study period (~ 1% difference) with respect to Scozzafava and Tallini (2001) monthly analysis, a reduction of approximately 9% of recharge value has been inferred during the last 20 years. This finding suggests an increase in the ETR component on water balance during the last twenty years, probably due to an increase in temperature as a possible effect of incoming climate change, as stated in recent research papers and reports.

Hartmann et al. (2017), for carbonate rock aquifers, simulated that for the end of the century (2080–2099) in European mountain regions, a decrease in annual precipitation of approximately − 14%, an increase in temperature of 4.9 °C and an increase in high rainfall events of + 8% are expected. The occurrence of the abovementioned conditions results in a decrease of 28% of infiltration with respect to the average current values of 500 mm/y.

The last Intergovernmental Panel on Climate Change report includes future scenarios on climate change effects. In detail, for the Mediterranean area, in the next 30 years, an increase in the temperature of approximately 1.5–3 °C is predicted, coupled with a decrease in rainfall and a shortening of the snow season that would start 2–4 weeks later and end 5 weeks earlier than the 1992–2012 average. These changes would obviously also imply some change in the recharge of the studied aquifer and in its water budget. Applying a simplified scenario based on the IPCC report (Intergovernmental Panel on Climate Change, 2021), it is possible to assume a present and future modification of the recharge rate involving the Gran Sasso aquifer.

Therefore, a simple modified scenario has been applied to TUR and THR for the period 2010–2020 and for 2020, one of the driest periods recorded in the last 20 years. The aim of these simulations is to verify whether the observed reduction in recharge is in line with expected climate scenarios; we do not intend to preview the real future spring discharge of the aquifer but only verify the consistency of observed changes and potential climate scenarios.

Specifically, the simulated scenario data include a rise in temperature of 1.5 °C (conservative condition) and a shortening of the snow season, which starts three weeks later (late November) and ends five weeks earlier (late March). In a conservative approach to the IPCC scenario, no change in average rainfall was applied.

Comparisons of the real and modified scenarios, named IPCC-TUR and IPCC-THR, are summarized in Tables 3 and 4. Both the IPCC-TUR and IPCC-THR show an increase in ETR, with a corresponding decrease in infiltration values.

In detail, for the simulated scenario of the 2010–2020 monitoring period, the IPCC-TUR shows an increase in ETR of approximately 5% and a similar consequent decrease in infiltration; the IPCC-THR shows an increase in ETR of 11% and a decrease in infiltration to 13%, in line with Hartmann et al.'s (2017) calculation. Moreover, the future scenario indicates that the snowfall component would decrease by more than 50%, strongly influencing the total recharge, which would decrease by 14% in IPCC-TUR and by 22% in IPCC-THR. This is due to the shortening of the snow season, which erases the contributions of snow recharge, at least in November and April.

The differences in recharge for this future scenario are higher in IPCC-THR than in IPCC-TUR. This is most likely due to the monthly increase in temperature, which strongly influences the ETR and infiltration estimation in both the cold and warm seasons.

For the driest conditions (applied to real 2020 data), the IPCC-TUR scenario shows an increase in ETR of approximately 10%, while infiltration decreases by approximately 11%. The IPCC-THR scenario highlights an increase in ETR of approximately 3% and a decrease in infiltration and recharge of approximately 8%. In both cases, the snow recharge decreases by 40%. In this scenario, there are no significant changes when applying either method, revealing a limited sensitivity of recharge value estimation by different methods in "extreme conditions", such as drought periods.

The application of the IPCC scenarios at the two different time periods, when adopting the most conservative conditions (limited changes in temperature, no changes in rainfall), confirms the outlook of a strong reduction in recharge due to snowmelt coupled with a

Table 3
Water balance results obtained for the IPCC future scenario for 2010–2020.

	TUR 2010–2020	IPCC-TUR 2010–2020	%	THR 2010–2020	IPCC-THR 2010–2020	%
P [mm]	984	984		984	984	
T [°C]	9.8	11.3		9.8	11.3	
ETR [mm]	450	476	+ 5%	513	572	+ 11%
R [mm]	2.8	2.8		2.8	2.8	
I [mm]	531	505	-5%	468	409	-13%
Q [m^3/s]	17.4	16.5	-5%	15.4	13.4	-13%
Snow [m^3/s]	3.9	1.8	-54%	3.9	1.8	-54%
Qtot [m^3/s]	21.3	18.3	-14%	19.3	15.2	-22%

Table 4
Water balance results obtained for the IPCC future scenario applied to the 2020 data.

	TUR 2020	IPCC-TUR 2020	%	THR 2020	IPCC-THR 2020	%
P [mm]	819	819		819	819	
T [°C]	10.2	11.7		10.2	11.7	
ETR [mm]	428	469	+ 10%	528	542	+ 3%
R [mm]	2.4	2.4		2.4	2.4	
I [mm]	389	348	-11%	298	274	-8%
Q [m^3/s]	12.8	11.4	-11%	9.8	9	-8%
Snow [m^3/s]	1.0	0.6	-40%	1.0	0.6	-40%
Qtot [m^3/s]	13.8	12	-13%	10.8	9.6	-11%

smaller but significant decrease in total recharge, especially in the 2010–2020 scenario.

The variations obtained from the last decade analyses (2010–2020) highlight the potential sensitivity of the Gran Sasso aquifer to climate variations, both on-going and potentially incoming in the future. This aspect focuses on a possible decrease in groundwater resource availability, which leads to a comprehensive review of resource management both in terms of drinking and other purposes.

5. Conclusion

Recharge evaluation in carbonate fractured and karstified aquifers is usually applied to wide hydrogeological basins or to single spring catchments, with reference to mean values of effective infiltration. Nevertheless, climate change effects and more widespread global changes (including human pressures such as withdrawals) are modifying the water budget of aquifers, affecting the total amount of renewable groundwater resources. While for single spring catchments, an updated evaluation of these resources is not difficult by hydrograph decomposition and/or tracer tests, at a larger aquifer scale, the shift to a distributed water budget analysis is mandatory to obtain representative values of effective recharge with time.

In this study, an accurate analysis has been performed recalculating the precipitation distributed with elevation (by 100 ×100 m cells on a total area of more than 1000 km^2) at annual and monthly scales. The last twenty years (2001–2020) have been considered, separating rainfall and snowmelt contributions to recharge. To limit the influence of the water budget method, three separate analyses were carried out from the same input data. At the annual scale, the Turc formula was applied (TUR), while at the monthly scale, the Thornthwaite method was selected (THR); a third method based on geological parameters (Aplis, APR) was adopted to ensure independence from empirical formulas. The obtained results offer several insights and perspectives for the future management of groundwater resources, as summarized below:

- Aquifer recharges calculated by the three different methods are similar when assessing for the reliability of the results; yearly mean infiltration ranges from 558 (THR) to 606 mm/y (TUR), with a method incidence lower than 10% (APR results in 594 mm/y);
- The snowmelt contribution to recharge seems to be significant, reaching 98 mm/y and is heavily dependent on the snow coverage distribution with space (elevation) and its persistence with time. The lowest snowmelt recharge accounted for 1.0 m^3/s (approximately 30 mm/y) in 2020, while the maximum input for 2010 resulted in 5.3 m^3/s (approximately 160 mm/y).
- Recharge variability during the twenty years (2001–2020) considered is noteworthy, ranging from a maximum higher than 800 mm/y (2013) to minimum values of approximately 300 mm/y (2006–2007 and 2020). This high variability of infiltration (>100%) with years confirms the need to assess the annual water budget, instead of assuming mean recharge values, to improve water resource management and to promote the adaptation of withdrawals to the natural oscillation of aquifer recharge;
- Recharge is obviously dependent on the ridge elevation, but it has been clarified that the influence of high-elevation areas increases during drought periods; conversely, these areas have a limited impact in rainy years, when low-elevation carbonate outcrops are able to contribute as much as the high-elevation areas to the infiltration process;
- Comparing calculated recharge with real spring discharge allows us to underline the resilience of the groundwater resources in the studied aquifer; in fact, discharge values are usually slightly higher than yearly calculated recharge for all methods; the overflow observed at springs with respect to calculated recharge is relevant for years affected by drought (or at least low-average infiltration years), testifying to a possible memory effect of the carbonate aquifer evident at the base-flow springs; this response confirms the aquifer hydrodynamic conditions, which favour a fracture-network groundwater flow with respect to fast-flow due to karst features, predominantly observed in high-elevation springs and/or during high-recharge periods;
- The natural resilience of groundwater flow is confirmed by the correlation of calculated recharge with delayed discharge at the south-eastern boundaries of the regional aquifer: the major springs fed by baseflow show a recharge/discharge correlation with a one to two year delay in response; such baseflow discharge allows the aquifer to compensate for a period of drought with a limited recharge rate, but at the same time, the aquifer risks recording a delayed extreme shortage in discharge conditions after a low-recharge period.

These findings, which offer an updated evaluation of both recharge amount and recharge/discharge mechanisms, have been used to build simple future scenarios considering the potential risk of climate change effects on the infiltration values and have obtained the following two main results:

- A conservative scenario based on limited expected changes (+1.5 °C and no rainfall depletion) highlights a significant reduction in rainfall recharge with negative effects on discharge (−5 to −13%) for an average year (based on 2010–2020 data) and similar depletion for a drought year (using 2020 data); consequently, a decreasing trend in infiltration is possible, which most likely has been ongoing for the last twenty years, when looking at the calculated infiltration for 2001–2020, which is lower than reference values based on 20th century data;
- A dramatic shortage in recharge due to snow cover reduction and snowmelt contribution is more than a possibility: built scenarios show more than −50% in snow recharge for average periods and approximately −40% for driest years (when snow infiltration is still limited), deeply affecting the expected total discharge of the aquifer, reaching −14/−22% with respect to actual conditions.

In summary, this study reveals that the renewable rate of groundwater resources, even under favourable hydrodynamic conditions with high resilience of baseflow discharge, is expected to significantly decrease in the future under conservative scenarios without changes in rainfall. Temperature increases and the consequent reduction in the contribution of snow to aquifer recharge are significant pressures, representing an elevated challenge for renewable groundwater resources and related human uses in regional carbonate fractured aquifers located in the main ridges, such as the Gran Sasso Mountains. The awareness of such a concrete risk requires immediate optimization measures, reflecting on the importance of water management in reducing vulnerability to climate change. Practically, withdrawals from wells would be modulated within seasons and years. In addition, following the worst scenario and only if necessary to preserve the environmental value of the territory included in a National Park, also spring withdrawals would be limited at least in drought periods. It is time to disprove the legend of endless water resources. Knowledge of recharge/discharge conditions can prevent potential emergency conditions and the resulting relevant and unjustified expenses required to cope with future, expected reductions in groundwater resources.

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CRediT authorship contribution statement

Valeria Lorenzi: Conceptualization, Methodology, Writing – original draft, Investigation, Visualization, Revision. **Chiara Sbarbati**: Conceptualization, Methodology, Formal analysis, Validation, Writing – original draft; **Francesca Banzato**: Conceptualization, Methodology, Investigation. **Alessandro Lacchini**: Conceptualization, Methodology, Data curation, Visualization. **Marco Petitta**: Conceptualization, Methodology, Formal analysis, Validation, Writing – original draft, Revision, Supervision, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101090.

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