

Differentiating groundwater recharge flowpaths in fault-controlled karstic aquifers (Gran Sasso range, Central Italy): Structural, hydrochemical and isotopic investigations on the highway tunnel drainage

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ABSTRACT

Study region: The Gran Sasso karst aquifer is one of the largest aquifers of Central Italy and a key drinking water resource. The system ($\sim 1000 \text{ km}^2$) is composed of fractured/karstified carbonate rocks influenced by a complex tectonic framework of thrusts and normal faults. Two parallel motorway tunnels (tapping $\sim 1.5 \text{ m}^3/\text{s}$ of groundwater for drinking purposes) provide a unique opportunity to observe flow conditions several kilometers below the ground.

Study focus: This study assesses the recharge mechanisms and flow dynamics of the fractured/karstified carbonate Gran Sasso aquifer using a multidisciplinary approach to improve drinking water withdrawal management and to contribute to the knowledge of recharge mechanisms in carbonate aquifers. It integrates a new characterization of the lithological/structural setting with discharge measurements, geochemical (major/trace elements) and isotopic data ($\delta^{18}\text{O}$, $\delta^2\text{H}$, ^3H and $^{87}\text{Sr}/^{86}\text{Sr}$) collected from 27 drainage points along the tunnels.

New hydrological insights for the region: Results reveal four overlapped recharge mechanisms, from fast to slow pathways, all interacting to varying degrees with the Meso-Cenozoic aquifer and with Quaternary deposits. Structural/lithological variability of permeability control recharge heterogeneity. At the basin scale, different recharge mechanisms produce homogeneous groundwater characteristics. At the local tunnel scale, infiltration heterogeneity could generate significant vulnerability with critical implication for protection and management. These findings enhance understanding of the Gran Sasso aquifer's dynamics and provide a reference model for fault-controlled fractured/karst systems.

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1. Introduction

Fractured and karst aquifers are complex underground labyrinths where groundwater flows at variable velocities through different flowpaths (Stephen and Worthington, 2009; Medici and West, 2021). In fault-controlled karstic aquifers (*sensu* Gori et al., 2024), the hydrogeological behavior of fault zones dramatically influences the development of karst features, the presence of groundwater divides and the groundwater flow direction. Their architecture dictates permeability, depending on low-permeability fault cores versus high-permeability fractured damage zones (Caine et al., 1996; Aydin, 2000; Bense et al., 2003; Petrella et al., 2025). Larger scale fault structures, including segmentation or multiple fault cores with overlapping damage zones (Faulkner et al., 2010), create structural heterogeneity impacting permeability. Rock permeability also varies with lithology, geological formations, fracture density and fault orientation, enhancing groundwater flow complexity for sure at local scale, with implications at regional scale. The cumulative effect of faults and rock permeability defines hydrogeological sub-basins. Snowmelt in mountainous recharge areas, characterized by coverage, persistence and contribution, is an additional variable (Hayashi, 2020; Lorenzi et al., 2022). Consequently, groundwater flow direction, entity, residence time, and thus its chemical/isotopic content reflects this complexity (White, 2019), especially in recharge zones. Hydrogeologists typically infer interaction among lithology, tectonics, and water flow from infiltration and discharge areas (Bonacci, 1993; Barbieri et al., 2005). However, understanding these dual-to-triple flow systems (fracture network, matrix permeability, and karst conduit - if any), is hindered by poor resolution of underground geology and unsaturated zone. Fold-and-thrust belt aquifers often display fluids of multiple origins (Barberio et al., 2021; Gori et al., 2023 and 2024), with variable groundwater velocities due to the variable properties of fractured rocks (Zimmerman and Bodvarsson, 1996; Schulze-Makuch et al., 1999; Berkowitz, 2002; Eaton et al., 2007; Krásný and Sharp, 2007; Neuman, 2008), strong influencing hydraulic gradients in fault-controlled karst systems (Celico et al., 2006; Fiorillo et al., 2012; Xu et al., 2018).

The main bottleneck in detailing groundwater flowpaths in fractured and karstified aquifers is the absence of internal observation points, aside from speleologically explored karst conduits and tracer tests (Goldscheider et al., 2008). Measurements are often limited to infiltration input and spring discharge, following a 'black-box' approach that averages final mixing, discharge regime, hydro-chemistry and isotopic composition, thereby hindering parameter characterization. Lumped parameters models offer simplified reservoir relationships (Cousquer and Jourde, 2022).

Effective management of karst aquifers, strategic drinking water sources (Parise et al., 2015; Stevanović, 2019), requires comprehensive aquifer study to mitigate risks (i.e., Mimi and Assi, 2009). Climate change further complicates recharge (Barbieri et al., 2023), with prolonged droughts, rainfall peaks, and altered snowmelt due to temperature rise significantly influencing karst aquifers (Lorenzi et al., 2023). Beyond natural evolution of karst aquifers, the overprint of human activities, such as the construction of underground structures (e.g., tunnel highways), can also change karst drainage properties (e.g., Tallini et al., 2014; Zini et al., 2015; Lv et al., 2020, 2022). In this framework, tunneling through fractured and partially karstified aquifers provides a unique "window" into groundwater flowpath. This allows for checking aquifer functioning and investigating parameters influencing groundwater inputs immediately under the water table in recharge zones, before flow becomes homogeneous towards regional base level discharge.

The Gran Sasso (GS) ridge in Central Italy exemplifies this. Two parallel motorway drainage tunnels, drilled in the '70 s, now tap approximately 1.5 m³/s groundwater for drinking purposes (Celico et al., 2005; Adinolfi Falcone et al., 2008; Amoroso et al., 2013). Drainage from numerous points and surrounding areas, including exploration boreholes, offers direct access to geological and hydrogeological useful information. This rare condition allows sampling groundwater over several kilometers underground, tracing changes in structural fault conditions, including thrusts as well, and fluid hydrochemistry. The GS example offers insights into regional water table conditions and tunnel-induced changes (located ~ 1000 m a.s.l.). Characterization of tunnel drainage points was very limited until new efforts in 2021–22 (Manetta, 2022), involving hydrogeochemical and isotopic analysis of twenty-seven drainage points coupled with lithological and structural review. The strategic role of the GS karst system stems from its high-quality water, limited anthropization, and significant groundwater volumes (Barbieri et al., 2005; Celico et al., 2005; Adinolfi Falcone et al., 2012; Amoroso et al., 2014; Tallini et al., 2014; De Luca et al., 2018).

This work represents an up-to-date characterization of the influence of lithological, structural, and hydrogeological variables on the superimposition of different recharge mechanisms in the GS karst aquifer. This approach has two main goals: a) optimizing understanding of dual/triple-flow aquifer systems by checking infiltrating groundwater components under the recharge zone, a difficult area to characterize; b) improving drinking withdrawal management.

This involves shifting from "passive" tapping to active management, by selecting single drainages based on renewable rate and residence time, addressing climate change scenarios, promoting sustainable groundwater use for drinking and enhancing pollution protection. Finally, GS aquifer results offer a reference for fault-controlled karst aquifer intersections, comparable to other karst aquifers with similar tectonics and shifting "drought & flood" climate conditions.

Usually, it is very difficult to assess recharge mechanisms inside fractured/karst aquifers, due to the lack of access points in the saturated zone below recharge areas. So, the tunnel drainage monitoring and the results we obtained can be interesting also for other potential fractured/karstified aquifers among the world.

2. Geological and hydrogeological settings and exploration of Gran Sasso tunnels

2.1. Lithostratigraphy and tectonic setting

The Gran Sasso (GS) range consists predominantly of Mesozoic–Cenozoic carbonate units stacked and transported toward the Laga Basin (Fig. 1; Adamoli et al., 1978 and references therein). Its structure, the highest morpho-structural culmination of the Apennines, is

defined by an upper and a lower NE-verging thrust (Calamita et al., 2004; Vezzani et al., 2010; Figs. 2–3; UT: Upper thrust). Geological mapping near the GS tunnels was conducted by Calembert et al. (1972a,b; 1974), Cardello (2008), and the Italian Geological Survey (Servizio Geologico d'Italia, 2010). The lithostratigraphy was revised by Cardello and Doglioni (2015), integrating previous schemes (e.g., Passeri et al., 2008; van Konijnenburg et al., 1998, van Konijnenburg et al., 1999), and later standardized (Cardello et al., 2022).

The GS evolution comprises: (1) Late Triassic–Early Jurassic rifting forming the “Umbrian palaeo-highs”; (2) Late Cretaceous–early Palaeogene westward tilting, possibly related to renewed extension; (3) Oligocene–Middle Miocene synsedimentary extension with partial fault reactivation; (4) Messinian foreland-directed thrusting, uplift, and erosion, preserving inherited Mesozoic geometries (Lucca et al., 2019; Rusciadelli et al., 2005); (5) earliest Pliocene foreland tilting and back-thrusting; and (6) Quaternary–present post-shortening extension producing NE–SW normal and WNW right-lateral transtensional faults (Demurtas et al., 2016). Major normal faults having significant impact on hydrogeology, as Valle Fredda Fault (VFF in Figs. 1–2) and Campo Imperatore Fault (CIF in Figs. 1–2) show multistage activity (Cardello and Doglioni, 2015) and bound valleys filled with Quaternary–Holocene deposits (Sanders et al., 2018 and references therein; Galli et al., 2021).

2.2. Hydrogeological setting

The GS karst aquifer extends over $\sim 1000 \text{ km}^2$ (Fig. 1) and exhibits high permeability due to intense fracturing and karstification mainly developed in recharge areas (Scozzafava and Tallini, 2001; Di Celso et al., 2005; Di Sabatino et al., 2005; Amoroso and Crescentini, 2010; Carucci et al., 2012; Tallini et al., 2013). Groundwater flow is controlled by facies distribution and fault systems with contrasting hydraulic conductivities, whereas regional aquicludes (e.g., siliciclastic deposits of the Laga Formation) define no-flow boundaries. The hydrogeological basin is well constrained at the thrust front, while its southern boundary is less distinct due to normal faults connecting with the Sirente and Morrone aquifers, allowing possible local seepage (Petitta and Tallini, 2002; Amoroso et al., 2013). Flow directions are guided by major tectonic discontinuities and hydraulic gradients.

Recharge is concentrated in the tectono-karstic endorheic Campo Imperatore Basin (1950–1650 m a.s.l.), sustained by high rainfall and snowfall. The aquifer feeds boundary springs with total discharge between 18 and 25 m^3/s (Petitta et al., 2022; Amoroso et al., 2011) and net infiltration of $\sim 600 \text{ mm}/\text{yr}$ (previous evaluations up to 700 mm/yr ; Lorenzi et al., 2022). Northern springs show

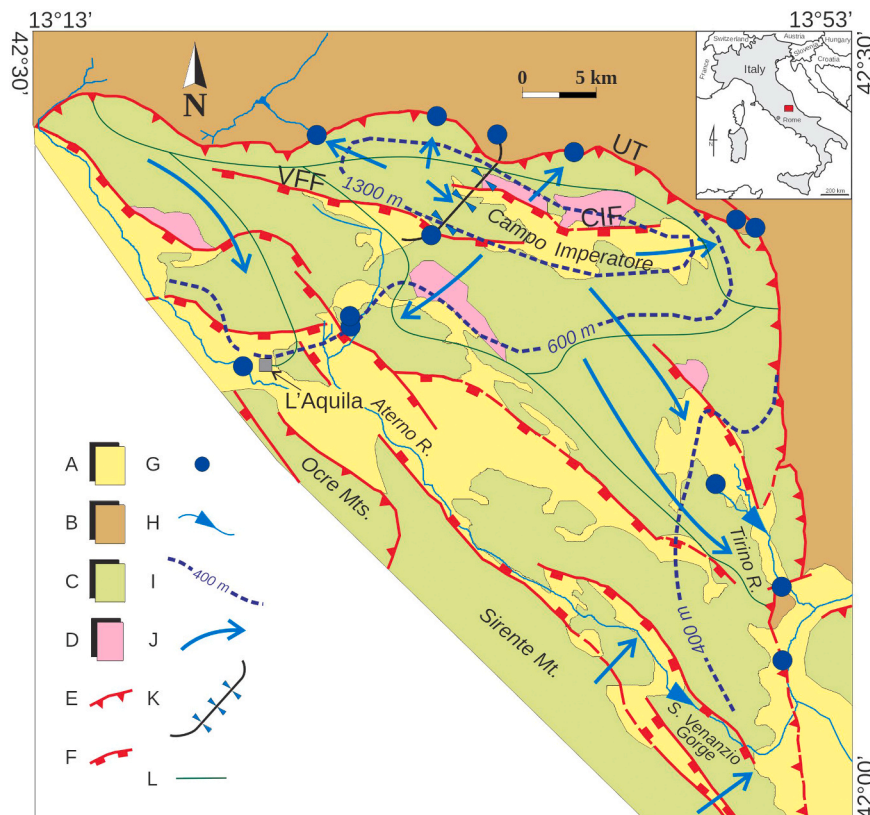


Fig. 1. Simplified hydrogeological setting of the Gran Sasso aquifer. A: Aquitard (continental detrital units of intramontane basins, Quaternary), B: aquiclude (terrigenous turbidites, Mio-Pliocene), C: aquifer (calcareous sequences, Meso-Cenozoic), D: low permeability bedrock (dolomite, upper Triassic), E: main thrust, F: main extensional fault, G: main spring, H: main streambed spring, I: piezometric head contours, J: groundwater flow direction, K: highway tunnel drainage, L: main watershed divided (modified from Lorenzi et al. 2022).

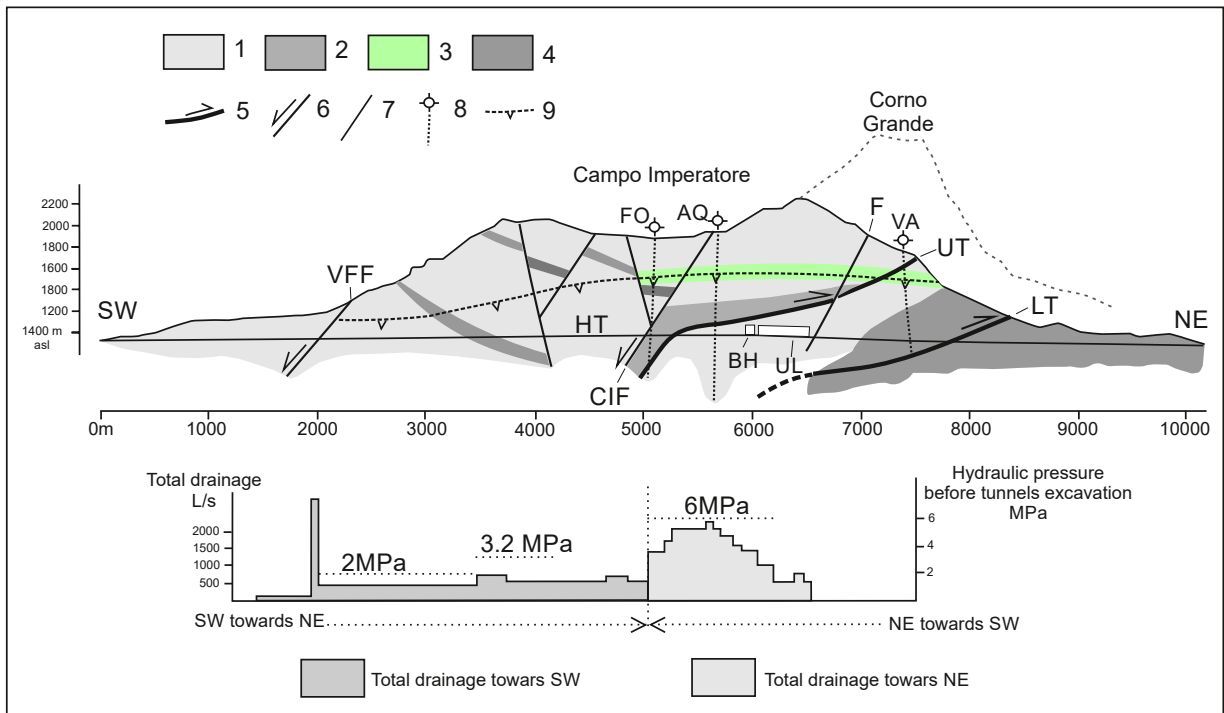


Fig. 2. Cross-section of Gran Sasso massif with hydrostatic pressure distribution before tunnel drainage. 1- slope Upper Cretaceous - Upper Jurassic succession; 2- neritic dolomite Upper Triassic *Dolomia Principale*; 3- paleokarst horizon; 4- terrigenous low-permeability lithologies; 5- main thrusts (UT: upper thrust; LT: lower thrust); 6- main normal fault (CIF: Campo Imperatore fault; VFF: Valle Fredda fault) with low permeability fault gauge; 7- minor high-angle normal fault (F behaves hydraulically as a drain); 8- deep boreholes (FO: Fontari; AQ: Monte Aquila; VA: Vaduccio); 9- water table before the tunnels excavation. Bottom: groundwater drainage during excavation (left Y-axis) and hydraulic pressure before excavation (right Y-axis); HT- highway; BH- borehole hall; UL- Gran Sasso underground laboratory (modified after Isaya et al., 2025).

marked seasonal variability ($\sim 2 \text{ m}^3/\text{s}$), whereas southern springs display stable base flow conditions ($\sim 20 \text{ m}^3/\text{s}$).

The drilling of the motorway tunnels and the National Nuclear Physics Laboratory underground laboratory (INFN) since the 1980s caused significant hydrogeological perturbations, including reduced spring discharge and piezometric lowering up to 600 m along the tunnel axis (Petitta and Tallini, 2002; Celico et al., 2005; Adinolfi Falcone et al., 2008). The system subsequently attained a new steady-state condition, with drainage now expressed by two anthropogenic springs (Ferracuti et al., 2006).

2.3. Subsurface exploration of Gran Sasso tunnels

The Gran Sasso (GS) motorway tunnels constitute a major engineering work that significantly altered the regional hydrogeological setting. The western (Assergi) and eastern (Casale San Nicola) portals are located at 958 m and 891 m a.s.l., respectively, with an internal highest point at $\sim 973 \text{ m a.s.l.}$ and a maximum rock overburden of $\sim 1000 \text{ m}$. The system consists of two parallel tunnels: tunnel A (Casale San Nicola–Assergi direction) and tunnel B (Assergi–Casale San Nicola direction), extending for a total length of $\sim 10.2 \text{ km}$.

Comprehensive geological and hydrogeological investigations preceded and accompanied drilling (Calembert et al., 1972a,b, 1974; Monjoie, 1975). Under the direction of P.G. Catalano, feasibility studies (1966–1968) defined the geological framework and a preliminary hydrogeological model. Subsequent investigations (1969–1986) included hydrological monitoring, tracer tests, and systematic measurement of drained waters. Between 1971 and 1973, three deep boreholes (FO, AQ, VA; Fig. 2) were drilled along the tunnel axis. From 1971 to 1980, 98 inner boreholes (totaling 14.5 km) and piezometric monitoring stations were installed (Fig. 2), significantly improving knowledge of transient subsurface conditions during excavation.

Excavation, initiated in 1969 and completed in 1980, was repeatedly slowed by high groundwater pressures recorded in boreholes (up to 6 MPa). Tunnel construction induced a marked reduction in spring discharge and triggered persistent groundwater drainage (Celico et al., 2005; Amoroso et al., 2014). In the following years, the system progressively reached a new hydrodynamic equilibrium (Petitta and Tallini, 2002; Amoroso et al., 2013). Current drainage rates are $\sim 0.45 \text{ m}^3/\text{s}$ on the Assergi side and $\sim 1.05 \text{ m}^3/\text{s}$ on the Casale San Nicola side (Adinolfi Falcone et al., 2008).

The INFN Gran Sasso Laboratories—comprising three experimental halls and an interferometric station—operate beneath $\sim 1300 \text{ m}$ of rock overburden, ensuring low-background conditions for rare-event physics experiments (Celico et al., 2005). The INFN underground laboratories, located within tunnel A approximately 6.25 km from the Assergi portal, contribute an additional discharge

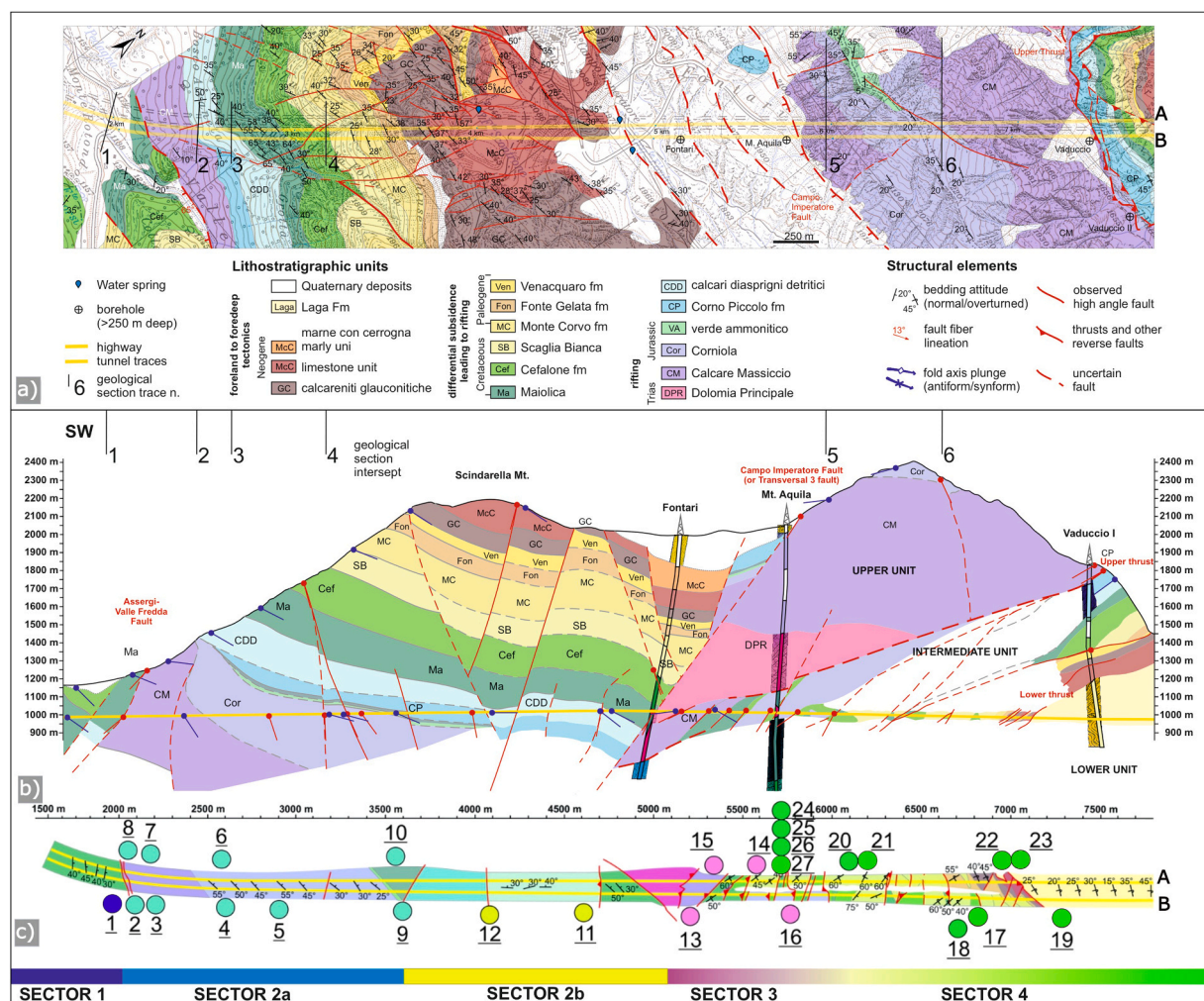


Fig. 3. a) Surface geological map of the motorway tracks near Valle Fredda (VVF in Fig. 2), Campo Imperatore and near Vaduccio borehole (VA in Fig. 2). Progressive 2000 and 8000 m from the western portal; b) – Geological cross section parallel to the tunnel B with sampling points and mapped bedding and fault dip attitudes, respectively represented by dark and red circles, respectively; c) Geological setting into the tunnel A and B with sampling localities (colored dots following subdivision into four sectors).

of $\sim 0.2 \text{ m}^3/\text{s}$. About half of this flow is conveyed to the Assergi portal and used for drinking purposes, while the remainder is diverted through a dedicated pipeline to the Casale San Nicola portal, where it is released into the surface hydrographic network.

3. Material and methods

A multidisciplinary approach was used in order to update and review the underground hydrostructural framework along the highway tunnels by means of structural geology and geochemical and isotopic analysis.

3.1. Review of the geological-structural framework

The revision of the geological-structural framework included: lithostratigraphic harmonization, detailed mapping over $\sim 7 \text{ km}^2$, reinterpretation of subsurface geology along both tunnels, a longitudinal section of tunnel B, and six transverse sections along tunnels. Hydrogeological sub-basins, defined by lithostratigraphic and tectonic compartmentalization of the regional aquifer, were identified through longitudinal and transverse analyses referenced to tunnel B (Fig. 3a, b).

Subsurface uncertainty was reduced by refining tunnel positioning, reinterpreting surface geology—particularly inherited Mesozoic structures—and cross-checking all sections, supported by satellite imagery (Google Earth Pro, 07/05/2024). The stratigraphic framework integrates new field data with published and archival sources (Servizio Geologico d'Italia, 2010; Cardello and Doglioni, 2015; Cardello et al., 2022), alongside topographic and geological maps, borehole data (Calembert et al., 1972a,b, 1974; Lunardi and Catalano, 1979), tunnelling reports (ANAS and INFN, 1996), interferometer excavation data (Catalano et al., 1986), and subsurface

maps (ANAS, 1981; ANAS and INFN, 1996).

The strata and fault attitudes were obtained from available measurements both in the underground and at the surface, including also minor faults. Of note, the tunnel geometry was taken from the geological cross-section of Catalano et al. (1986), as well as the elevations reached by tunnel B. The longitudinal geological section was drawn on the topographic profile, incorporating the geological information between progressive 1500 and 8000 m. Total fault displacement was calculated along several geological cross-sections. Perpendicular cross-sections were obtained by cross-referencing surface and tunneling data with the projection of interpreted data along the longitudinal section. The accuracy of the deep structural interpretation depends on the geological maps and is in the order of a few tens of meters.

3.2. Sampling and laboratory analysis

In October 2021, a sampling survey of 27 drainage points was carried out along the tunnels (Fig. 3c). The sampling period, corresponding to the depletion phase of the aquifer, allows to verify the groundwater drainage characteristics in absence of active infiltration inputs from rainfall or snowmelt, recording the baseflow contribution. The selection of samplings was based on geological sections, structural discontinuities and site accessibility. Many of the sampling points refer to draining channels inside the aqueduct conduit located beneath the highway surface; other samples refer instead to active drainage boreholes along or in the proximity of the tunnel sides.

The on-site measurement of electrical conductivity (EC ref. temp.: 25°C), temperature, and pH were carried out using the WTW Multi 3420 multiparametric probe, with accuracies of 1 µS/cm, 0.1 °C, and 0.01 pH unit, respectively. Water samples for major and trace element analyses were filtered using 0.45 µm membrane filters, and the latter were acidified on-site using ultrapure HNO₃. Water samples for isotopic analyses ($\delta^{18}\text{O}$, $\delta^2\text{H}$, ^3H and $^{87}\text{Sr}/^{86}\text{Sr}$ ratio) were collected without any treatments.

Anions and cations were determined through ion chromatography using Dionex ICS 5000 and Dionex ICS 1100 chromatographs at the Geochemistry Laboratory of the Department of Earth Sciences at Sapienza University of Rome. Bicarbonate ions were measured through titration with 0.05 N HCl solution. The ionic balance error for each sample was within $\pm 5\%$. Trace elements were analyzed using an ICP-MS spectrometer (X Series 2 Thermo Fisher Scientific Waltham, MA, USA). Blanks, standard solutions, and sample dilutions were prepared using ultrapure water (Millipore, Milli-Q, 16 MW cm), and an internal standard (Rh) was added to correct for ICP-MS instrumental drift. The analytical accuracy of this method ranges between 2% and 5%.

The water stable isotope ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) were measured in delta units per mil (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW). The analytical precision is about $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 1\text{‰}$ for $\delta^2\text{H}$. Tritium (^3H) content was determined using an electrolytic enrichment and liquid scintillation counting method, and the values are reported in Tritium Units (TU). The strontium isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) was normalized to NIST SRM 987 and the external reproducibility (2σ) was better than ± 0.00002 . All the isotope analyses were performed at IT2E Isotope Tracer Technologies Europe Srl in Milan, Italy.

The flow measurements into the tunnel, carried out in both aqueduct conduits located beneath the highway surface, are inherited from Manetta (2022). The flow measurements were performed during geochemical and isotopic monitoring.

4. Results

4.1. Geological and structural summary

This chapter presents the geological and hydrogeological framework of the GS tunnels, emphasizing how tectonic structures control groundwater flow (Fig. 3a). The carbonate succession hosting the regional aquifer is organized into a fold-and-thrust structure, which is responsible for diverging groundwater flow in different sectors. The aquitards include formations rich in clay minerals or with low porosity such as the *Verde Ammonitico*, the so-called *Scaglia oligocenica* (Venacquaro formation or *Scaglia Cinerea Detritica*), and the *Marne con cerroghna*. In the northeast, to the right of the map, the upper thrust (UT in Figs. 1–2) juxtaposes the Lower Jurassic of the upper unit on the overturned Upper Jurassic-Middle Miocene succession of the intermediate tectonic unit, having limited permeability. This unit is then juxtaposed to the lower unit (acting as aquiclude), via the lower thrust, which was encountered during tunnel excavations (Lunardi and Catalano, 1979). Along the tunnels, the massif was divided into four hypothetical sectors (S1–S4) from southwest to northeast based on structural-geological information. Sector S1 (progressive 400–2000 m) is mainly unsaturated at tunnel elevation and bounded by the Valle Fredda Fault (VFF in Figs. 1–2) which juxtaposes Cretaceous over Lower Jurassic units and prevents lateral flow. Sector S2 (progressive 2000–4890 m) represents the main drainage zone, and at its end it is intersected by the Campo Imperatore Fault (CIF in Figs. 1–2), a roll-over anticline with associated horst-and-graben structures. S2 is subdivided into S2a and S2b, separated by the *Verde Ammonitico* aquitard. Campo Imperatore Fault has a multiple hydrogeological role. Sector S3 (progressive 4890–5500 m) corresponds to the hanging wall of the upper thrust, where fractures dominate flow and the thrust potentially acts as a low-permeability boundary, which as can be seen from the different structures encountered in the two tunnels, varies laterally due to transpressive structures overprinting the transpressive structures. Sector S4 (progressive 5500–7830 m) lies beyond the lower thrust, with permeability totally controlled by fractures and faults, and juxtaposed against upright Laga Formation strata. Tunnel excavation and borehole data indicate that thrust-related fault gouges locally reduce the transmissivity of the rock mass (Catalano et al., 1986). In addition, the intermediate overturned Scaglia unit, together with the marly layers, acts as a partial aquitard, limiting groundwater flow. In the 6000–7000 m interval, the alternation of calcarenites (Cefalone Formation) and marly layers (Scaglia Bianca and Monte Corvo Formations) produces variable permeability conditions, ranging from moderate to low.

Fig. 3a and 3b also present a comprehensive review of the stratigraphic and tectonic units initially reported by ANAS (1981) and

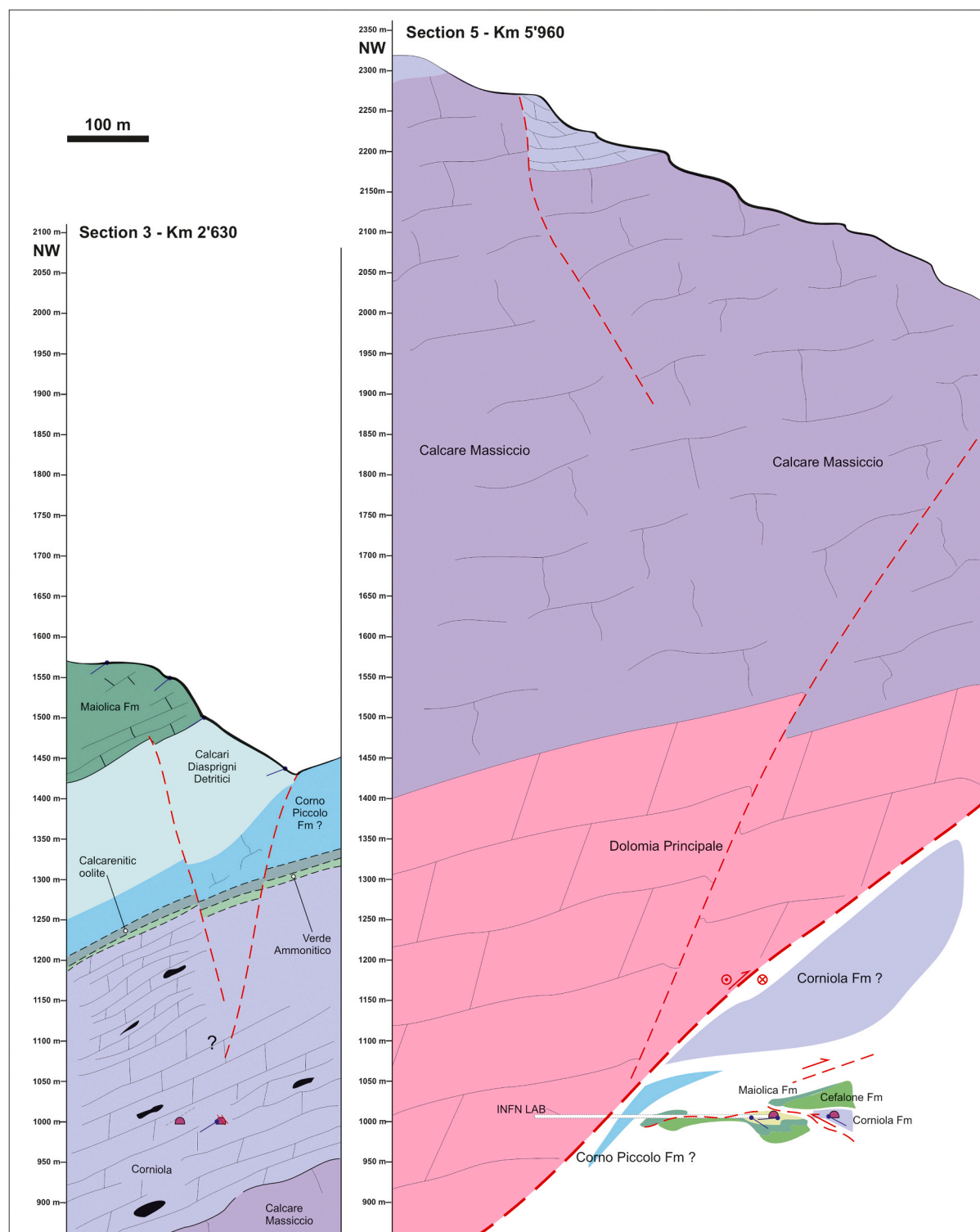


Fig. 4. The transversal geological cross sections numbered 3 and 5 are delineated perpendicular to the tunnels. No vertical or lateral exaggeration is applied. Refer to Fig. 3 for the location. The section of the tunnels is represented by the two apertures located at an elevation of approximately 1000 m above sea level. In Section 5, the INFN Labs projection is included (white bar located on the left of the tunnels).

ANAS and INFN (1996). The Assergi-Valle Fredda Fault, at the boundary S1/S2, is ENE-striking and downthrown the succession of about 1 km, juxtaposing Cretaceous units over the Lower Jurassic *Calcare Massiccio* (Fig. 3). The fault structure is made of an asymmetric 20-meter-thick fault core with gouge seams, mostly developed in the footwall, and an approximately 20 m thick damage zone of strongly fractured carbonates. In terms of hydrogeology, the gouge impedes the flow of groundwater laterally, while the fractured damage zone likely promotes higher transmissivity. To the northwest, the *Campo Imperatore* Fault exhibits a curved geometry being about E-striking at surface and about NE-striking at depth in the tunnel. As illustrated in Fig. 3, the *Campo Imperatore* Fault is associated with a roll-over anticline fold towards the northeast. This fold is further cross-cut by synthetic and antithetic faults resulting in a horst-and-graben structure. The same thrust faults, as reported in tunnel data, are often accompanied by fault gouges ranging from a few decimeters to several meters in thickness Catalano et al. (1986). These are semi-incoherent cataclasites that are locally composed of argillites produced by friction along fault planes. The gouge can significantly reduce hydraulic transmissivity between portions of the aquifer, acting - at least locally - as an aquitard. The shear zone, situated between the main overthrusts, exhibits a transpressive duplex structure whose distribution changes from place to place across the two tunnels, indicating a deformation with rotational movements across transpressive structures and plunging folds. Between progressive 5000 and 5500 m in the tunnel, the area is affected by both normal and reverse faults, having opposite results in groundwater flow, hindering or facilitating drainages. This intermediate unit is then juxtaposed in S4 to the Laga formation up-right strata by the lower thrust.

Six new transverse cross-sections constrained lateral lithology variations and hydrostructural features. Among those, the two most significant are shown: cross section 3 and cross section 5 (Fig. 4). Cross-section 3 (progressive 2630 m, sector 2a) highlights thick variations and high-angle faults in the Jurassic succession, with possible implications on groundwater flow in this sector. Cross-section 5 (progressive 5960 m, between sectors 3 and 4), near the INFN laboratories, crosses the upper thrust. The succession beneath the main thrust includes marly units and shear zones, which could act as aquitards, but it is also crossed by discrete high-angle faults. Near the surface, the upper unit crops out, involving the Triassic–Jurassic neritic carbonate, this is a frontal transpressive structure intersected by minor high-angle faults.

4.2. Geochemical results

Supplementary Table S1 shows all geochemical data and the statistical indicators such as average, minimum and maximum values, and standard deviation (STD), including physico-chemical parameters, major and trace elements, and isotopes for the 27 sampling sites.

Calcium and Bicarbonate are the most prominent ions, with average values of 25.8 ppm and 139.6 ppm, respectively. Among the trace elements, Strontium and Barium show the highest concentrations, with values of 51.7 ppb and 30.6 ppb, respectively. The STD values for physical-chemical parameters and major ions are relatively low. Fig. 5A displays a preliminary geochemical characterization of groundwater samples. The dominant geochemical facies are Calcium-Bicarbonate. No significative differences can be observed among the tunnel sectors, but samples distribution reveals some possible slight mixing effects.

Fig. 5B illustrates the ratios of trace elements and physical-chemical parameters. Considering the most represented cations, the Sr/

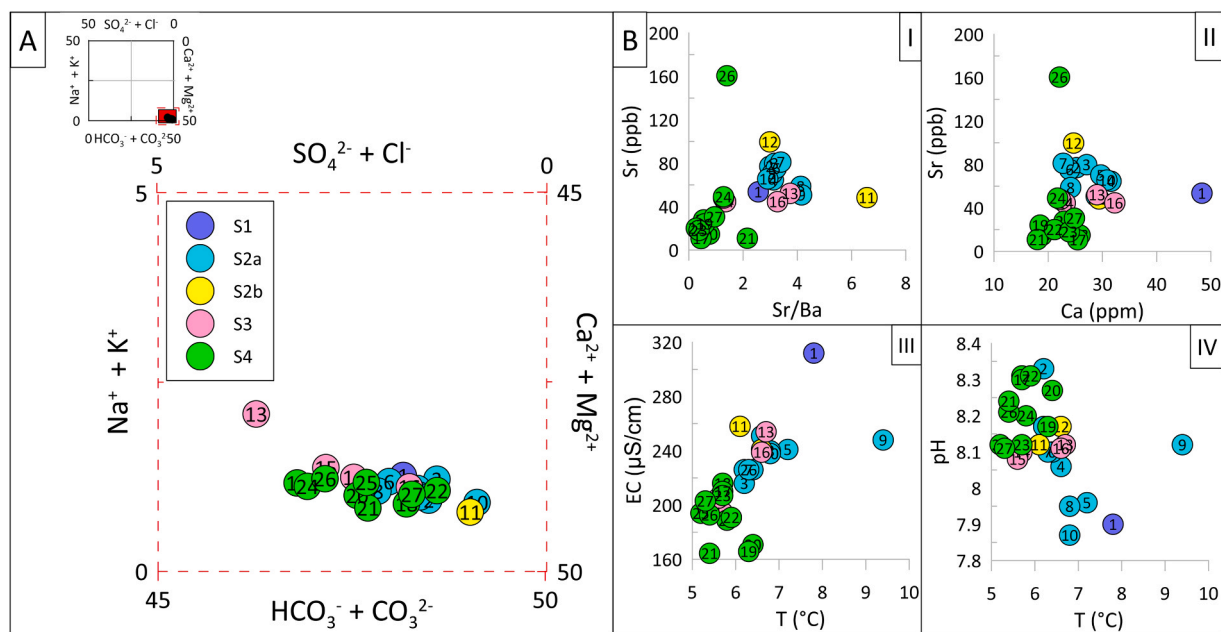


Fig. 5. A) Langelier-Ludwig diagram; B) I Sr/(Sr/Ba) ratio, II Sr/Ca ratio, III Electrical Conductivity (EC)/Temperature (T) ratio, IV pH/Temperature (T) ratio. For colors and the sample locations see Fig. 3.

(Sr/Ba) and Sr/Ca ratios (Fig. 5B I, II), show a preliminary differentiation among the tunnel sectors. Except for sample 26, which represents an outlier with respect to the Strontium means concentration of the samples analysed (not a relevant geochemical outlier with respect to their absolute concentration), the southern and central sectors (S1, S2a, S2b and S3) exhibit higher concentrations of Strontium and Calcium compared to S4 and higher values of Electrical Conductivity and Temperature (Fig. 5B III). The pH/Temperature ratio, illustrated in Fig. 5B IV, does not provide additional insights due to minimal variations in pH among the samples.

Fig. 6A shows the results of stable water isotope analysis ($\delta^{18}\text{O}$ and $\delta^2\text{H}$), with a significant correlation with the local meteoric water lines adopted for the GS massif by Celico et al. (1984) and Barbieri et al. (2005). A wide range of fractionation was observed in S4 (represented by green circles in Fig. 6A). The samples from sectors S1, S2a, S2b and S3 displayed intermediate isotopic values. Based on these data, specific isotopic vertical gradients were calculated, and the equation provided by Barbieri et al. (2005) for determining Computed Isotope Recharge Elevation (CIRE) was applied (Fig. 6B). The highest CIRE values were calculated for samples 18, 20, 24, 25, and 26 of S4 (> 2050 m a.s.l.). An isotopic elevation of approximately 2000 m a.s.l. was recorded for S2a and S2b (excluding samples 7, 10 and 12) and S3. On the other hand, sample 1 from S1 and, 19, 21, 22, 23 and 27 from S4 exhibited the lower CIRE values (<1950 m a.s.l.), with the lowest values for sample 17.

Conversely, the analysis of the strontium isotopes shown in Fig. 7A, clearly distinguishes two groups. Group I has values between 0.70911 and 0.70951, and Group II has values between 0.70789 and 0.70854. In Fig. 7B, the results of the tritium isotopes are shown. These are distributed around an average value of 3.6 TU, with a maximum of 5.5 TU and a minimum of 1.5 TU. The values obtained in the different sectors revealed a significant homogeneity with some spike-like anomalies (i.e., sample 8). The northern sectors (S4) have greater uniformity, while the southern sector (S1 and S2a) exhibits two distinct travel times: samples 7, 8, 9, and 10 are characterized by slower circulation ("older water"), while samples 1, 2, 4, 5, and 6 are subjected to faster travel times ("younger water").

4.3. Tunneling discharge measurements

The discharge measurements were carried out in both aqueduct channels located beneath the highway surface (red and black lines respectively in Fig. 8) and their cumulative values are shown (green line in Fig. 8). Due to a simple topographic divide located around the progressive 5100 m, water is flowing in two directions in the parallel tunnels. This situation results in two growing lines from the center (5100 m) towards both exits (Assergi and Casale San Nicola). Additionally, the cumulative discharge flow during the excavation period (from the tunnel's peak to the Assergi entrance) is presented (blue line in Fig. 8). The distribution of tunnel drainage results in a flow towards the Assergi portal of about 370 l/s measured at progressive 2130 m (draining mainly sectors S2a and S2b) and about 600 l/s towards the Casale San Nicola portal at progressive 6950 m (draining mainly sector S3 with some inputs from S4). By considering these increments, valuable information can be derived about the most hydrop productive sectors of the aquifer near the tunnel. In particular, the major flow increments occur in two specific sectors of the entire tunnel: from progressive 3000 to 2100 m, approximately 280 l/s (sector 2a), and from progressive 5400 m to 7000 m (end of S3 and S4), approximately 530 l/s. Slight discharge increments, totaling around 80 l/s, are observed between progressive 5000 m and 3600 meters, which corresponds to the S2b sector, where low-permeability rocks occur.

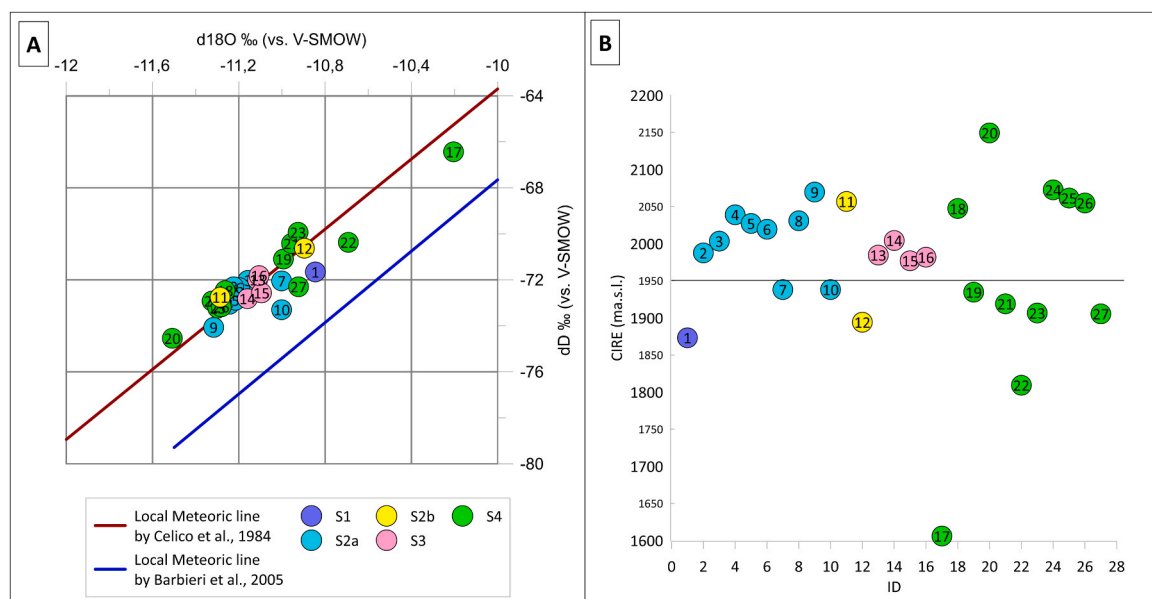


Fig. 6. A) Correlation between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values and meteoric water lines (blue line from Celico et al., 1984; red line from Barbieri et al., 2005); B) Computed Isotope Recharge Elevation (CIRE) for each water sample. The horizontal black line corresponds to the maximum elevation of Campo Imperatore Plain. For colors and the sample locations see Fig. 3.

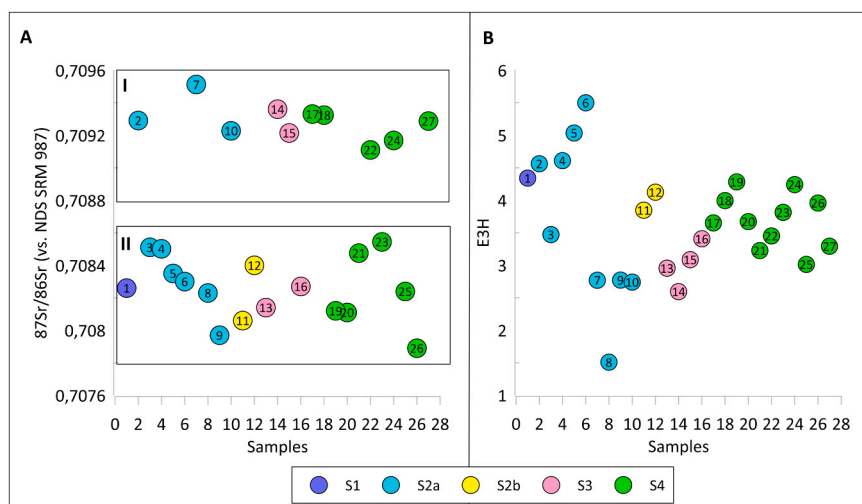


Fig. 7. A) Strontium and B) Tritium isotopes data. For colors and sample location see Fig. 4.

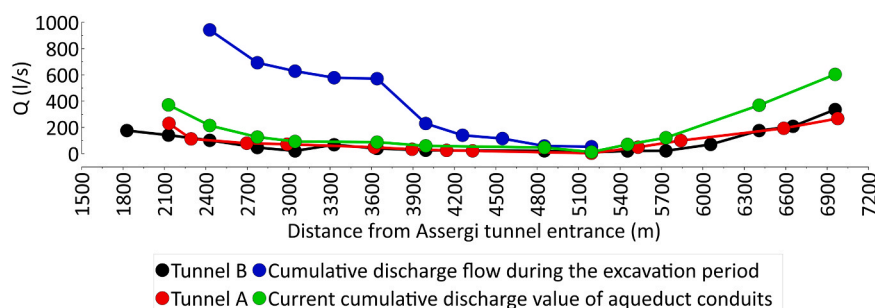


Fig. 8. Discharge measurements in the tunnel inside the aqueduct conduits located beneath the highway surface.

5. Discussion

Assembling the results of the revised geo-structural setting with hydrogeochemical and isotopic information, an updated hydrodynamic setup of groundwater flow along the highway tunnel drainages is proposed. The results obtained revealed several hydrodynamic aspects of the natural recharge of the aquifer and of their arrival along the highway tunnel.

First, attempts to distinguish the water circulating within the previously identified geological-structural sectors of the GS aquifer based on major ion concentrations were unsuccessful, due to the common limestone behavior, resulting in a general calcium-bicarbonate water (Fig. 5). Thus, all along the tunnel, the groundwater does not show distinctive geochemical characteristics except for low concentration of Strontium and Calcium and low temperature in the northern sector, suggesting a lower degree of water-rock interaction compared with the southern sectors. This hypothesis is confirmed by tritium values, which are relatively high for sector 4, confirming a significant fast flow component due to the presence of a significant enhancement of the expected low permeability due to fracture-flow in this sector. The lower degree of water-rock interaction could be due to the presence of fractures with large openings and, in more detail, could be related to the occurrence of a fault-controlled highly permeable paleo-karstic zone lying at an elevation of about 1600 m (Adinolfi Falcone et al., 2008).

The isotopic analyses of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ demonstrated a strong correlation with the local meteoric water line adopted for the GS aquifer, so no external processes (i.e., evaporation and/or water-rock interaction) affect the infiltrating water. The stable isotopes show scattered values and do not provide a clear distinction between previously identified geological-structural sectors along the tunnels (Fig. 6), even if the latter could have distinct mean altitudes of recharge areas. In detail, sector 1 and sector 2a are expected to receive recharge from elevation not higher than 1500 m a.s.l. This value is lower than those obtained from the CIRE, which results is above 2000 m a.s.l. However, considering the elevation span of the entire aquifer (from 1150 to 2650 m a.s.l.) and that the most important recharge events occur during the autumn/winter season, this incongruity could be due to the influence of the snow fraction over the rain contribution. In addition, groundwater drained in sectors 3 and 4 shows scattered stable isotope values, spread over 500 m of different altitudes. These results only highlight differentiated flowpaths of groundwater intercepted by the tunnels, in agreement with a flow driven by fracture/faults collecting infiltrating waters from different surface areas. Thus, stable isotopes reveal different mechanisms of recharge and drainage at the tunnel scale, but they are not the best option to trace the hydrological pathways within

catchments in this case.

The Tritium content reveals the presence of fast groundwater flow for most samples, with some differences among sectors (Fig. 7). In fact, the values are consistent with present-day rainfall measured in the surrounding areas (4–6 TU; Petrella et al., 2009; Boschetti et al., 2013). The low tritium activity obtained in sample 8 (1.5 TU) in the southern sector (S2), could be the effect of sampling water that flows through rocks having low hydraulic conductivity (Lunardi and Catalano, 1979) and thus could present a long transit time.

The analysis of the strontium isotope ratio has allowed the identification of two separate groups, indicating the presence of two distinct sources within the aquifer. Relevant information can be argued from the $^3\text{H}/(^{87}\text{Sr}/^{86}\text{Sr})$ ratio (Fig. 9) and by combining the two isotopes. The Strontium isotope results provide valuable information regarding the water-rock interaction process. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of dissolved strontium in groundwater reflects the isotopic composition of the host rock (McArthur et al., 2012). The results presented in Fig. 9 allowed the identification of two distinct groups of samples in which the sectors are randomly distributed. One group represents groundwater that has interacted with Mesozoic carbonate units, while the other is associated with Cenozoic (up to Quaternary) units, in accordance with the observed reduction of infiltration values with time.

The comparison between discharge increments measured during tunnel excavation and current measurements suggests that the same drainage pathways remain active, although with reduced flow rates (Fig. 8). Integration of the updated geological-structural framework with hydrogeological and hydrogeochemical investigations has clarified that groundwater is concentrated toward the two most productive sectors. In the southern sector (S2a), flow is facilitated by the outcrop of highly permeable rocks such as *Calcare Massiccio* and *Corniola*, while in the northern sector (S3), circulation is enhanced by highly tectonized rocks beneath the upper thrust. Other sectors (e.g., S2b and S4) are dominated by lower-permeability layers, which locally act as aquitards and constrain flow to fractures and faults.

Fault gouges reported are particularly effective in compartmentalizing the aquifer: the thickness of the *Assergi-Valle Fredda* Fault is about 20 m and was able to produce a difference in piezometric load of about 200 m (Lunardi and Catalano, 1979). Fault thickness locally presents a fault core twice as thick (Demurtas et al., 2016). Further, the fault core of the upper thrust is also well developed, and it crosses a variety of lithologies, maintaining a thickness of the principal slip surface ranging from 0.5 to 2 m throughout the area (Leah et al., 2018) and behaves as a low-permeability barrier (Copia et al., 2017). At the same time, fault zones commonly show significant variation in complexity along strike or down dip (Faulkner et al., 2010) related to changing in their structure. Moreover, in the case of GS massif it is of the noteworthy importance that the Quaternary extensional fault system often cuts the continuity, and the integrity of the pre-existing thrust faults (D'Agostino et al., 1998). Thus, the hydrogeological behavior of the fault zones can locally change (also laterally, see Fig. 4), even if their role at the regional scale remains the same.

Based on structural and geochemical results, four main recharge mechanisms were identified:

- i) rapid infiltration along major fault zones, conveying seasonal rainfall quickly to the saturated zone with limited water-rock interaction;
- ii) discharge of relatively old groundwater with low tritium content, representing a slow-flow component stored for several years within low-permeability layers before reaching the tunnel drainages;
- iii) a slow-flow contribution characterized by interaction with older carbonate formations (as indicated by strontium isotopes) and minor interaction with deposits filling the endorheic plain;
- iv) rapid recharge involving interaction with recent carbonate and Quaternary detrital/cover deposits during infiltration, likely flowing through surface karst systems and the underlying fracture-karst network before quickly discharging into the tunnel drainage system.

The updated model indicates that the Gran Sasso aquifer beneath the motorway tunnels exhibits a complex circulation controlled by rock fracturing, fault zones, and the permeability of different lithologies. Groundwater flows predominantly from the recharge areas as Campo Imperatore, *Monte Aquila*, and *Monte Scindarella*, toward the tunnel drainage system, with two distinct velocities: slow flow through microfracturing and faster flow along major faults (Fig. 10).

With respect to the classical dual-flow characterizing karst aquifers, we identify several elements of novelty in our study. One of the novelties is methodological, related to the possibility of checking dual velocity through isotopic signatures (the unique possibility to track groundwater characteristics exactly below the infiltration area). Usually, dual components are identified by tracers or by hydrograph discharge analysis.

Another clear novelty is about the components of dual flow: there are no underground karst features in this aquifer, and consequently, the dual flow is related to a microfracturing/matrix component, and to a fault/high permeability zone occurring along some main faults. Consequently, the role of the faults is prominent for hydrogeology, both as they represent low-permeability limits of the aquifer (creating hydrogeological sub-basins), but also as drivers of fast flow from surface towards the saturated zone and the related drainage in the tunnel strips.

The third significant finding is related to the resource protection and improved management of the drinking groundwater: the drained water into the tunneling is coming from different flowpaths, not directly related to the sectors outcropping into the tunneling (meaning the hydrogeological sub-basins are not directly responsible for groundwater flow into the tunnels). In fact, the tunnel drainage is due to the interception of groundwater coming from different flowpaths, despite the main infiltration zone being the same (Campo Imperatore and surrounding areas). This appears to be very promising for future management and protection of the resources, requiring accurate monitoring at the tunnel scale.

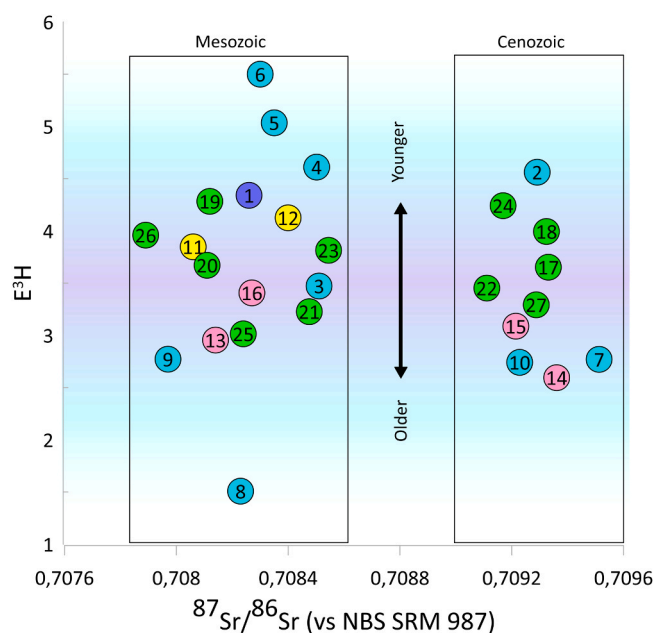


Fig. 9. Tritium vs Strontium isotope plot. For colors and the sample locations see Fig. 3.

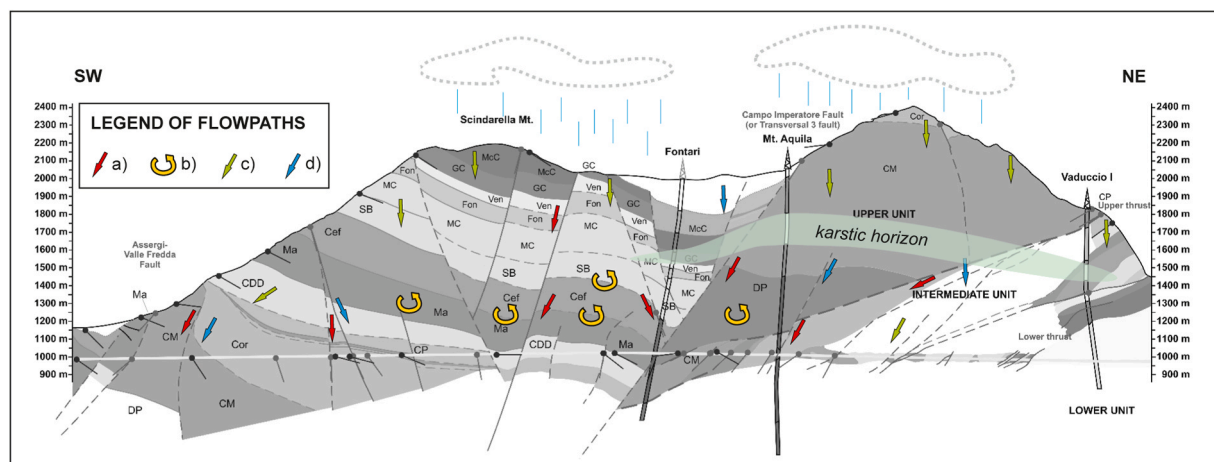


Fig. 10. Conceptual model of groundwater flow based on the arrival into the tunnel drainage; a) fast infiltration flowpath through main fault zones; b) slow-flow aliquot, trapped in the low-permeability layers; c) slow-flow contribution interacting with the recent carbonate deposits and possibly with recent deposits; d) fast arrival of groundwater similarly interacting with recent carbonate and detrital/coverage deposits, moving through karst systems and the underlying fracture-karstic network.

6. Conclusions

Recharge mechanisms of the fractured and karstified carbonate aquifer of the Gran Sasso massif were investigated through surveys along the highway tunnel drainages. Although major ion chemistry is relatively homogeneous due to the common calcareous origin of the massif, trace elements and isotopic data (especially tritium and strontium) reveal complex recharge processes. Groundwater circulation is controlled by the interaction between the fracture network, the karst system, and lithological heterogeneity, including permeable platform carbonates and more compartmentalized base-of-slope deposits. Structural analysis indicates that high-angle transtensive faults disrupt the fold-and-thrust transpressive architecture, promoting localized vertical flow and mixing respect with the different geological sectors of the tunnels, consistent with the geochemical variability observed among the 27 sampled drainage points.

The isotopic results shed light on flowpaths from the surface infiltration to the saturated zone, confirming both the significant contribution of the endorheic basin of Campo Imperatore and the influence of the main normal fault zones.

The occurrence of different flowpaths within the tunnel drainage system does not directly correspond to the geologically and structurally defined sectors intercepted by the tunnel. This mismatch highlights the complexity of infiltration processes in the unsaturated zone and groundwater circulation within the shallow saturated zone.

This study highlights both practical and scientific implications for the Gran Sasso aquifer. Recharge occurs predominantly through karst outcrops, including the Campo Imperatore endorheic plain (Lorenzi et al., 2023), but infiltrating waters follow multiple tectonically controlled pathways to reach the saturated zone. At the regional scale, this variability is largely smoothed out: groundwater mixes during flow toward major discharge zones, resulting in geochemically homogeneous baseflow that supports sustained minimum discharge.

At the scale of the tunnel drainage system, however, the heterogeneity of recharge flowpaths increases vulnerability. Rapid flow along fractures and faults can quickly transport potential contaminants. Tunnel discharge depends on the superposition of fast and slow flow components, requiring a detailed assessment of the origin and quantity of drained water. This underscores the practical need to monitor each drainage point, including piezometric head and discharge, to evaluate the contribution of different flowpaths and ensure safe and sustainable management of this drinking water resource. From a scientific perspective, the identification of multiple flowpaths is significant for understanding fractured and karst aquifers. It shows that groundwater homogenization occurs after recharge reaches the saturated zone, whereas variability primarily affects infiltration pathways. These insights are also important for evaluating aquifer recharge under climate change, as tunnel drainage monitoring provides rare access to subsurface dynamics that are otherwise difficult to observe.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marco Petitta reports financial support was provided by EU Framework Programme for Research and Innovation in the Mediterranean Area (PRIMA) programme. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2026.103360](https://doi.org/10.1016/j.ejrh.2026.103360).

Data availability

Data will be made available on request.

References

- Adamoli, L., Bertini, T., Chiocchini, M., Deiana, G., 1978. Ricerche geologiche sul Mesozoico del Gran Sasso d'Italia (Abruzzo). Evoluzione tettonico-sedimentaria dal Trias superiore al Cretaceo inferiore dell'area compresa tra il Corno Grande e S. Stefano di Sessanio (F. 140 Teramo). [Geological research on the Mesozoic era of Gran Sasso d'Italia (Abruzzo). Tectonic-sedimentary evolution from the Upper Triassic to the Lower Cretaceous in the area between Corno Grande and S. Stefano di Sessanio (F. 140 Teramo)]. *St. Geol. Cam.* 5, 7–17.
- Adinolfi Falcone, R., Falgiani, A., Parisse, B., Petitta, M., Spizzico, M., Tallini, M., 2008. Chemical and isotopic ($\delta^{18}\text{O}$ ‰, $\delta^2\text{H}$ ‰, $\delta^{13}\text{C}$ ‰, ^{222}Rn) multi-tracing for groundwater conceptual model of carbonate aquifer (Gran Sasso INFN underground laboratory - central Italy). *J. Hydrol.* 357, 368–388.
- Adinolfi Falcone, R., Carucci, V., Falgiani, A., Manetta, M., Parisse, B., Petitta, M., Rusi, S., Spizzico, M., Tallini, M., 2012. Changes on groundwater flow and hydrochemistry of the Gran Sasso carbonate aquifer due to the 2009 L'Aquila earthquake. *Ital. J. Geosci.* 131, 459–474.
- Amoruso, A., Crescentini, L., 2010. Limits on earthquake nucleation and other pre-seismic phenomena from continuous strain in the near field of the 2009 L'Aquila earthquake. *Geophys. Res. Lett.* 37, 10307.
- Amoruso, A., Crescentini, L., Petitta, M., Rusi, S., Tallini, M., 2011. Impact of the 6 April 2009 L'Aquila earthquake on groundwater flow in the Gran Sasso carbonate aquifer, Central Italy. *Hydrol. Process* 25, 1754–1764.
- Amoruso, A., Crescentini, L., Petitta, M., Tallini, M., 2013. Parsimonious recharge/discharge modeling in carbonate fractured aquifers: the groundwater flow in the Gran Sasso aquifer (Central Italy). *J. Hydrol.* 476, 137–146.
- Amoruso, A., Crescentini, L., Martino, S., Petitta, M., Tallini, M., 2014. Correlation between groundwater flow and deformation in the fractured carbonate Gran Sasso aquifer (INFN underground laboratories, central Italy). *Water Resour. Res.* 50, 4858–4876.
- ANAS, 1981. Geological surface survey - Assergi - Casale San Nicola section, Gran Sasso section (A24–A25 motorways). Geological map, scale 1:5,000. Survey by. L. Calembert (1974); Geological cross-section, scale 1:5,000 by P.G. Catalano.
- ANAS, INFN, 1996. Completion and adjustment of the structures of the Gran Sasso Nuclear Physics Laboratory – Final project: update of the original project in implementation of the opinion of the *Consiglio Superiore dei Lavori Pubblici*. Part A Basic Stud. Res. Gen. Rep. 1–17.
- Aydin, A., 2000. Fractures, faults, and hydrocarbon entrapment, migration and flow. *Mar. Pet. Geol.* 17, 797–814.
- Barberio, M.D., Gori, F., Barbieri, M., Boschetti, T., Caracausi, A., Cardello, G.L., Petitta, M., 2021. Understanding the origin and mixing of deep fluids in shallow aquifers and possible implications for crustal deformation studies: San Vittorino plain, central Apennines. *Appl. Sci.* 11, 1353.

- Barbieri, M., Boschetti, T., Petitta, M., Tallini, M., 2005. Stable isotope (^2H , ^{18}O and $^{87}\text{Sr}/^{86}\text{Sr}$) and hydrochemistry monitoring for groundwater hydrodynamics analysis in a karst aquifer (Gran Sasso, Central Italy). *Appl. Geochem.* 20, 2063–2081.
- Barbieri, M., Barberio, M.D., Banzato, F., Billi, A., Boschetti, T., Franchini, S., Gori, F., Petitta, M., 2023. Climate change and its effect on groundwater quality. *Environ. Geochem. Health* 45, 1133–1144.
- Bense, V.F., Van den Berg, E.H., Van Balen, R.T., 2003. Deformation mechanisms and hydraulic properties of fault zones in unconsolidated sediments; the Roer Valley Rift System, The Netherlands. *Hydrol. J.* 11, 319–332.
- Berkowitz, B., 2002. Characterizing flow and transport in fractured geological media: a review. *Adv. Water Resour.* 25, 861–884.
- Bonacci, O., 1993. Karst springs hydrographs as indicators of karst aquifers. *Hydrol. Sci. J.* 38, 51–62.
- Boschetti, T., De Felice, V., Celico, F., 2013. The Pozzo del Sale Groundwaters (Irpina, Southern Apennines, Italy): origin and mechanisms of salinization. *Aquat. Geochem.* 19, 303–322.
- Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zones architecture and permeability structure. *Geology* 24, 1023–1028.
- Calamita, F., Ben M'Barek, M., Di Vincenzo, M., Pelorosso, M., 2004. The Pliocene thrust system of the Gran Sasso salient (Central Apennines, Italy). In: Pasquarè, G., Venturini, C. (Eds.), *Mapping Geology in Italy*. APAT Dipartimento Difesa del Suolo, Servizio Geologico d'Italia. S.E.L.C.A., Firenze, pp. 227–234.
- Calembert, L., Catalano, P.G., Conato, V., Lambrecht, L., Monjeie, A., 1972a. Observations dans le massif du Gran Sasso (Apennin central). [Observations in the Gran Sasso massif (central Apennines)]. *C. R. Acad. Sc. Paris* 274, 2013–2015.
- Calembert, L., Catalano, P.G., Conato, V., Lambrecht, L., Monjeie, A., 1972b. Le sondage de Fontari dans le massif du Gran Sasso (Apennin central). [Fontari's survey in the Gran Sasso massif (central Apennines)]. *C. R. Acad. Sc. Paris* 274, 3065–3068.
- Calembert, L., Catalano, P.G., Conato, V., Lambrecht, L., Monjeie, A., 1974. Le sondage Vaduccio II dans le massif du Gran Sasso (Apennin central). [The Vaduccio II survey in the Gran Sasso massif (central Apennines)]. *C. R. Acad. Sc. Paris* 279, 1237–1243.
- Cardello, G.L., 2008. *Struttura del fianco occidentale del Massiccio del Gran Sasso d'Italia*. Master Thesis. Università La Sapienza, Roma (1–163 pp., <http://www.dst.uniroma1.it/biblioteca/>).
- Cardello, G.L., Doglioni, C., 2015. From Mesozoic rifting to Apennine orogeny: The Gran Sasso range (Italy). *Gondwana Res.* 27, 1307–1334.
- Cardello, G.L., Tomassetti, L., Cornacchia, I., Mancini, A., Mancini, M., Mazzini, I., Rusciadelli, G., Capezzuoli, E., Lorenzi, V., Petitta, M., Cavinato, G.P., Girotti, O., 2022. The Tethyan and Tyrrhenian margin record of the Central Apennines: a guide with insights from stratigraphy, tectonics, and hydrogeology. *GFT&M* 14, 1–113.
- Carucci, V., Petitta, M., Aravena, R., 2012. Interaction between shallow and deep aquifers in the Tivoli Plain (Central Italy) enhanced by groundwater extraction: a multi-isotope approach and geochemical modeling. *Appl. Geochem.* 27, 266–280.
- Catalano, P.G., Cavinato, G.P., Salini, F., Tozzi, M., 1986. Analisi strutturale nei laboratori dell'I.N.F.N. del Gran Sasso d'Italia. *Mem. Soc. Geol. Ital.* 35, 647–655.
- Celico, F., Petrella, E., Celico, P., 2006. Hydrogeological behavior of some fault zones in a carbonate aquifer of Southern Italy: an experimentally based model. *Terra Nova* 18, 308–313.
- Celico, P., Gofiantini, R., Koizumi, M., Mangano, F., 1984. Environmental isotope studies of limestone aquifers in central Italy. *Proceedings of International Symposium on Isotope Hydrology in Water Resource Development*, I.A.E.A., Vienna.
- Celico, P., Fabbrocio, S., Petitta, M., Tallini, M., 2005. Hydrogeological impact of the Gran Sasso motor-way tunnels (Central Italy). *GGA* 1, 157–165.
- Copia, L., Plastino, W., Nisi, S., Ciarletti, M., Povinec, P.P., 2017. ^{226}Ra and uranium isotopic ratios characterization into the Gran Sasso aquifer, Italy. *J. Radioanal. Nucl. Chem.* 311, 385–393.
- Cousquer, Y., Jourde, H., 2022. Reducing uncertainty of karst aquifer modeling with complementary hydrological observations for the sustainable management of groundwater resources. *J. Hydrol.* 612, 128130.
- D'Agostino, N., Chamot-Rooke, N., Funicello, R., Jolivet, L., Speranza, F., 1998. The role of pre-existing thrust faults and topography on the styles of extension in the Gran Sasso range (central Italy). *Tectonophysics* 292, 229–254.
- De Luca, G., Di Carlo, G., Tallini, M., 2018. A record of changes in the Gran Sasso groundwater before, during and after the 2016 Amatrice earthquake, central Italy. *Sci. Rep.* 8, 1–16.
- Demurtas, M., Fondriest, M., Balsamo, F., Clemenzi, L., Storti, F., Bistacchi, A., Di Toro, G., 2016. Structure of a normal seismogenic fault zone in carbonate: the Vado di Corno Fault, Campo Imperatore, Central Apennines (Italy). *J. Struct. Geol.* 90, 185–206.
- Di Celso, G.M., Spizzico, M., Tallini, M., 2005. Studio idrochimico multitemporale delle acque sorgive dell'acquifero carsico del Gran Sasso (Italia centrale) per un affinamento del modello idrochimico concettuale. [Multitemporal hydrochemical study of spring waters from the Gran Sasso karst aquifer (central Italy) for refinement of the conceptual hydrochemical model]. *GGA* 2, 420–428.
- Di Sabatino, V., Manetta, M., Sciannambio, D., Spizzico, M., Tallini, M., 2005. Il radon come tracciante delle acque sorgive finalizzato alla vulnerabilità degli acquiferi carbonatici complessi: l'esempio del gruppo sorgivo del Rio Arno (Gran Sasso, Italia centrale). [Radon as a tracer of spring waters for assessing the vulnerability of complex carbonate aquifers: the example of the Rio Arno Spring group (Gran Sasso, central Italy)]. *GGA* 2, 413–419.
- Eaton, T.T., Anderson, M.P., Bradbury, K.R., 2007. Fracture control of ground water flow and water chemistry in a rock aquitard. *Groundwater* 45, 601–615.
- Faulkner, D., Jackson, C., Lunz, R., Schlische, R., Shipton, Z., Wibberley, C., Withjack, M., 2010. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *J. Struct. Geol.* 32, 1557–1575.
- Ferracuti, L., Marinelli, G., Rusi, S., 2006. Idrogeologia e monitoraggio delle sorgenti carsiche del Tavo (massiccio carbonatico del Gran Sasso) e loro implicazioni nella gestione dell'emergenza torbida. [Hydrogeology and monitoring of the karst springs of Tavo (Gran Sasso carbonate massif) and their implications for turbidity emergency management]. *GGA* 3, 47–52.
- Fiorillo, F., Revellino, P., Ventafridda, G., 2012. Karst aquifer draining during dry periods. *JCKS* 74, 148–156.
- Galli, P., Galderisi, A., Messina, P., Peronace, E., 2021. The Gran Sasso fault system: Paleoseismological constraints on the catastrophic 1349 earthquake in Central Italy. *Tectonophysics* 822, 229156.
- Goldscheider, N., Meiman, J., Pronk, M., Smart, C., 2008. Tracer tests in karst hydrogeology and speleology. *IJS* 37, 27–40.
- Gori, F., Paternoster, M., Barbieri, M., Buttitta, D., Caracausi, A., Parente, F., Sulli, A., Petitta, M., 2023. Hydrogeochemical multi-component approach to assess fluids upwelling and mixing in shallow carbonate-evaporitic aquifers (Contursi area, southern Apennines, Italy). *J. Hydrol.* 618, 129258.
- Gori, F., Barberio, M.D., Barbieri, M., Boschetti, T., Cardello, G.L., Petitta, M., 2024. Groundwater–rock interactions and mixing in fault-controlled karstic aquifers: a structural, hydrogeochemical and multi-isotopic review of the Pontina Plain (Central Italy). *Sci. Total Environ.* 951, 175439.
- Hayashi, M., 2020. Alpine hydrogeology: the critical role of groundwater in sourcing the headwaters of the world. *Groundwater* 58, 498–510.
- Isaya, D., De Luca, G., Di Carlo, G., Guerriero, V., Martorana, R., Tallini, M., 2025. Hydroseismograms at Gran Sasso aquifer, central Italy, for earthquake hydrology studies. *Sci. Rep.* 15, 13162.
- van Konijnenburg, J.H., Wernli, R., Bernoulli, D., 1998. Tentative biostratigraphy of Paleogene plantik foraminifera in thin-section, an example from the Gran Sasso d'Italia (Central Apennines, Italy). *Eclogae Geol. Helv.* 91, 203–216.
- van Konijnenburg, J.H., Bernoulli, D., Mutti, M., 1999. Stratigraphic architecture of a Cretaceous to lower Tertiary Carbonate base-of-slope succession: Gran Sasso d'Italia (Central Apennines, Italy). 63. SEPM, Special Publication, pp. 291–315.
- Krásný, J., Sharp, J.M. (Eds.), 2007. *Groundwater in Fractured Rocks: IAH Selected Paper Series*, Vol. 9. CRC Press.
- Leah, H., Fondriest, M., Luca, A., Storti, F., Balsamo, F., Di Toro, G., 2018. Coseismic extension recorded within the damage zone of the Vado di Ferruccio Thrust Fault, Central Apennines, Italy. *J. Struct. Geol.* 114, 121–138.
- Lorenzi, V., Sbarbati, C., Banzato, F., Lacchini, A., Petitta, M., 2022. Recharge assessment of the Gran Sasso aquifer (Central Italy): Time-variable infiltration and influence of snow cover extension. *J. Hydrol. Reg. Stud.* 41, 101090.
- Lorenzi, V., Barberio, M.D., Sbarbati, C., Petitta, M., 2023. Groundwater recharge distribution due to snow cover in shortage conditions (2019–22) on the Gran Sasso carbonate aquifer (Central Italy). *Environ. Earth Sci.* 82, 206.
- Lucca, A., Storti, F., Balsamo, F., Clemenzi, L., Fondriest, M., Burgess, R., Di Toro, G., 2019. From submarine to subaerial out-of-sequence thrusting and gravity-driven extensional faulting: Gran Sasso Massif, Central Apennines, Italy. *Tectonics* 38, 4155–4184.

- Lunardi, P., Catalano, P.G., 1979. Gran Sasso. Il traforo autostradale. [Gran Sasso. The highway tunnel]. Eds. COGEFAR S.p.A. Milano.
- Lv, Y., Jiang, Y., Hu, W., Cao, M., Mao, Y., 2020. A review of the effects of tunnel excavation on the hydrology, ecology, and environment in karst areas: current status, challenges, and perspectives. *J. Hydrol.* 586, 124891.
- Lv, Y., Jiang, J., Chen, L., Hu, W., Jiang, Y., 2022. Elaborate simulation and predication of the tunnel drainage effect on karst groundwater field and discharge based on Visual MODFLOW. *J. Hydrol.* 612, 128023.
- Manetta, M., 2022. Studio geologico-idrogeologico-idrochimico e relazione geologica per il progetto di fattibilità tecnica ed economica della messa in sicurezza del sistema idrico del Gran Sasso. [Geological, hydrogeological, and hydrochemical study and geological report for the technical and economic feasibility project for securing the Gran Sasso water system]. Unpublished Report, 124 pp.
- McArthur, J.M., Howarth, R.J., Shields, G.A., 2012. Strontium Isotope Stratigraphy. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), *A Geological Timescale 2004*. Cambridge University Press, Cambridge, pp. 96–105.
- Medici, G., West, L.J., 2021. Groundwater flow velocities in karst aquifers; importance of spatial observation scale and hydraulic testing for contaminant transport prediction. *Environ. Sci. Pollut. Res.* 28, 43050–43063.
- Mimi, Z.A., Assi, A., 2009. Intrinsic vulnerability, hazard and risk mapping for karst aquifers: a case study. *J. Hydrol.* 364, 298–310.
- Monjoie, A., 1975. Hydrogéologie du massif du Gran Sasso (Apennin central). [Hydrogeology of the Gran Sasso massif (central Apennines)]. *Coll. Pubbl. Fac. Sci. Appl. Univ.* 53, 1–60.
- Neuman, S.P., 2008. Multiscale relationships between fracture length, aperture, density and permeability. *Geophys. Res. Lett.* 35, L22402.
- Parise, M., Ravbar, N., Zivanović, V., Mikszewski, A., Kresic, N., Mádl-Szőnyi, J., Kukurić, N., 2015. Hazards in karst and managing water resources quality. In: Stevanovic, Z. (Ed.), *Karst aquifers - Characterization and Engineering*. Springer International Publishing, pp. 601–687.
- Passeri, L., Ciarapica, G., Leonardi, F., Reggiani, L., Venturi, F., 2008. The Jurassic succession in the western part of the Gran Sasso Range (Central Apennines, Abruzzo, Italy). *Boll. Soc. Geol. Ital.* 127, 141–149.
- Petitta, M., Tallini, M., 2002. Groundwater hydrodynamic of the Gran Sasso Massif (Abruzzi): New hydrological, hydrogeological and hydrochemical surveys (1994–2001). *Boll. Soc. Geol. Ital.* 121, 343–363.
- Petitta, M., Banzato, F., Lorenzi, V., Matani, E., Sbarbati, C., 2022. Determining recharge distribution in fractured carbonate aquifers in central Italy using environmental isotopes: snowpack cover as an indicator for future availability of groundwater resources. *Hydrol. J.* 30, 1619–1636.
- Petrella, E., Naclerio, G., Falasca, A., Buccì, A., Capuano, P., De Felice, V., Celico, F., 2009. Non-permanent shallow halocline in a fractured carbonate aquifer, southern Italy. *J. Hydrol.* 373, 267–272.
- Petrella, E., Pizzati, M., Severini, E., Ferragionio, M.R., Polimeno, M., Balsamo, F., 2025. Multiple fault strands in carbonate rocks control groundwater circulation in tectonically active areas, Monte Marine Fault, central Apennines, Italy. *J. Hydrol.* 653, 132738.
- Rusciadelli, G., Viandante, M.G., Calamita, F., Cook, A.C., 2005. Burial-exhumation history of the central Apennines (Italy), from the foreland to the chain building: thermochronological and geological data. *Terra Nova* 176, 560–572.
- Sanders, D., Ortnier, H., Pomella, H., 2018. Stratigraphy and deformation of Pleistocene talus in relation to a normal fault zone (central Apennines, Italy). *Sediment. Geol.* 373, 77–97.
- Schulze-Makuch, D., Carlson, D.A., Cherkauer, D.S., Malik, P., 1999. Scale dependency of hydraulic conductivity in heterogeneous media. *Groundwater* 37, 904–919.
- Scozzafava, M., Tallini, M., 2001. Net infiltration in the Gran Sasso Massif of central Italy using the Thornthwaite water budget and curve-number method. *Hydrol. J.* 9, 461–475.
- Servizio Geologico d'Italia, 2010. Geological Map of Italy at the Scale 1:50.000, F. 349. Gran Sasso d'Italia. ISPRA, Roma. Available at (<https://www.isprambiente.gov.it/Media/carg/349 GRANASSO/Foglio.html>).
- Stephen, R., Worthington, H., 2009. Diagnostic hydrogeologic characteristics of a karst aquifer (Kentucky, USA). *Hydrol. J.* 17, 1665.
- Stevanović, Z., 2019. Karst waters in potable water supply: a global scale overview. *Environ. Earth Sci.* 78, 662.
- Tallini, M., Parisse, B., Petitta, M., Spizzico, M., 2013. Long-term spatio-temporal hydrochemical and ²²²Rn tracing to investigate groundwater flow and water-rock interaction in the Gran Sasso (central Italy) carbonate aquifer. *Hydrol. J.* 21, 1447–1467.
- Tallini, M., Adinolfi Falcone, R., Carucci, V., Falgiani, A., Parisse, B., Petitta, M., 2014. Isotope hydrology and geochemical modeling: new insights into the recharge processes and water-rock interactions of a fissured carbonate aquifer (Gran Sasso, central Italy). *Environ. Earth Sci.* 72, 1957–1971.
- Vezzani, L., Festa, A., Ghisetti, F.C., 2010. Geology and tectonic evolution of the Central-Southern Apennines, Italy. In: *Geological Society of America (Eds.), Geological Society of America Special Paper* 469, 2pp. 1–56.
- White, W.B., 2019. *Hydrogeology of karst aquifers*. Academic Press.
- Xu, B., Ye, M., Dong, S., Dai, Z., Pei, Y., 2018. A new model for simulating spring discharge recession and estimating effective porosity of karst aquifers. *J. Hydrol.* 562, 609–622.
- Zimmerman, R.W., Bodvarsson, G.S., 1996. Hydraulic conductivity of rock fractures. *Transp. Porous Med.* 23, 1–30.
- Zini, L., Chiara, C., Franco, C., 2015. The challenge of tunneling through Mediterranean karst aquifers: the case study of Trieste (Italy) The planning of large-scale infrastructures in karst areas. *Environ. Earth Sci.* 74, 281–295.