Giornale di Geologia Applicata 1 (2005) 157 –165, doi: 10.1474/GGA.2005-01.0-16.0016

Hydrogeological impact of the Gran Sasso motor-way tunnels (Central Italy)

Pietro Celico[1], Silvia Fabbrocino[1], Marco Petitta[2] and Marco Tallini[3]

[1] Department of Geophysics and Volcanology, University of Naples Federico II
[2] Department of Earth Sciences, University of Rome "La Sapienza"
[3] Department of Structural, Water and Soil Engineering, University of l'Aquila

ABSTRACT. Effects of underground infrastructures on the hydrogeological performance of carbonate aquifers are the objective of the paper, that in particular deals with Gran Sasso mountain, Central Italy, where motor-way tunnels were built. Prediction consequences of construction on groundwater flow can be carried out at different levels, depending on available data and scale of analysis. A case study of a tunnel crossing carbonate ridges, characterized by very heterogeneous and complex hydrogeological features, is reported taking into account geological, stratigraphical and structural setting. Effective review of geological, hydrogeological and geochemical data points out effects of tunnels on groundwater resources and reservoirs, and lead to some conclusions concerning the feasibility of a third tunnel. In particular, it is shown that only an accurate collection and synthesis of geological, structural and hydrogeological data, either at large scale or at small scale, can optimise design and construction of underground infrastructures and mitigate hydrogeological impact.

Key terms: Fractured aquifers, Groundwater drainage, Underground works, Water table depletion

Foreword

The construction of underground structures always raises geological, geotechnical, hydrogeological, technological and environmental issues. A carefully built and realistic conceptual physical model can simulate the response of the system to external events and thus optimise the design and construction of large underground infrastructures, both in technical-structural terms (construction timescales and costs) and from the standpoint of mitigation of their environmental impact in the short and long term.

Tunnels, although being built for different uses, may drain groundwater even after completion of their lining. In some instances, it is extremely difficult or impracticable to restore the original hydrodynamic equilibrium, with consequent risks of exhaustion of springs, change in the relations with adjacent hydrogeological structures, depletion of groundwater reserves, etc. Tunnel construction also can alter water supply for drinking, irrigation and industrial uses, with major economic and social repercussions on wide neighbouring areas.

In this context, hydrogeological surveying and monitoring activities (preceding, concurrent with and following tunnel construction) are a fundamental tool to assess the effects induced on water resources and to select the most appropriate actions of prevention of hydrogeological risks and/or of restoration of the hydrogeological equilibrium.

The assessment of the impact of the above structures on the environment and, namely, on water resources, should be preventive. However, the complexity of the phenomena at stake and, in some cases, the extent of the area involved do not always contribute to creating a uniform picture of future scenarios. As a result, pre- and post-construction monitoring can help guide and change the proposed projects in order to meet specific land management requirements.

The Gran Sasso motor-way tunnels epitomise the issues arising from construction of large underground structures, since the combination of multiple and concurrent factors (tunnels of considerable extent, construction of underground scientific laboratories, drainage of the basal aquifer with involvement of its permanent reserves, consequent reduction of discharges from the springs supplied by the aquifer) has interfered with wide portions of the aquifer, altering its water supply also in the long term (ALLOCCA *et alii*, 2003).

Furthermore, in the case of Gran Sasso, post-construction monitoring can help elucidate the consequences of the tunnels and provide inputs to the planning of further projects, such as the construction of a third tunnel, which is expected in the near future.

Hydrogeological Setting

The Gran Sasso hydrogeological unit extends over an area of about 700 km^2. It consists of fractured and karstified carbonates and is part of a larger hydrogeological unit that incorporates the nearby Mt. Sirente carbonate ridge (CELICO, 1978).

The Gran Sasso ridge is made up of transitional facies lithotypes (dolomites, limestones, marly limestones, marls), most of which outcrop along its northern, eastern and southern boundaries, as well as of calcareous-dolomitic terms, which are dominantly located in its south-eastern sector.

To the North and East, the permeability boundaries of the above unit coincide with the areas where Meso-Cenozoic carbonate series tectonically overlap synorogenetic turbiditic terrigenous deposits. In fact, the Gran Sasso structural setting has a wide fault-propagation-fold in its northern sector (corresponding to its main thrust fault), as well as a number of monoclines, which are downthrown by NW-SE-trending normal faults in its southern sector (GHISETTI & VEZZANI, 1983; BIGI *et alii*, 1991; VEZZANI & GHISETTI, 1998).

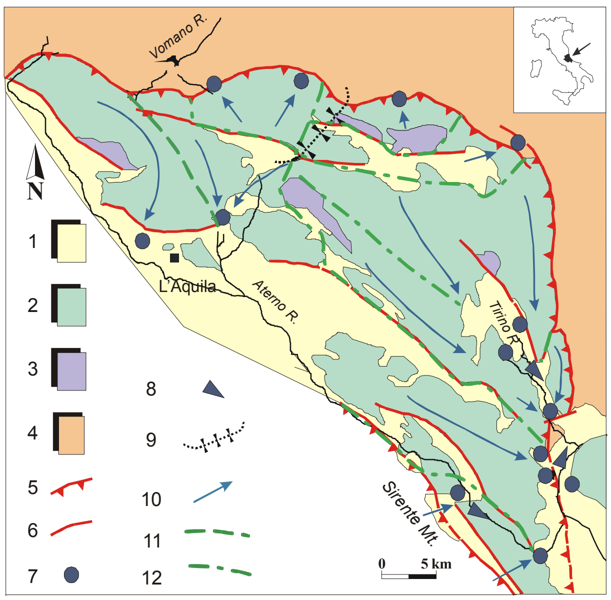

FIG. 1 - Gran Sasso hydrogeological unit (Central Italy). 1 - aquitard (continental clastic deposits of intra-montane basins, Quaternary); 2 - aquifer (carbonate sequences of platform - including reef - and slope-to-basin lithofacies, Mesozoic-Cenozoic); 3 - low permeability substratum (dolomite, upper Triassic); 4 – aquiclude (terrigenous turbidites, Mio-Pliocene); 5 - overthrust; 6 - normal fault; 7 - main spring; 8 - linear spring; 9 – motor-way tunnel drainage; 10 – main groundwater flowpaths; 11- groundwater divide (no flow boundary); 12 – groundwater divide (with seepage).

Extensional tectonic movements in Plio-Pleistocene times gave rise to intra-montane basins, occasionally endorheic, which were recently filled with detrital and alluvial deposits. On the south-western side, the permeability boundaries of the Gran Sasso sub-unit consist of the above-mentioned detrital and alluvial deposits, whose permeability is generally low. The endorheic basin of Campo Imperatore, inside the Gran Sasso ridge, is a preferential recharge area, since it is subject to concentrated infiltration. Thanks to high mean precipitation on the basin (estimated at roughly 1,000 mm/yr; FARRONI *et alii*, 1999; SCOZZAFAVA & TALLINI, 2000) and to its high permeability (owing to fractures and karst features), the hydrogeological unit has a mean recharge of over 700 mm/yr (BONI *et alii*, 1986).

The tectonic setting has direct influence on the underground hydrodynamics of the carbonate massif, which consists of a number of intercommunicating basins, with piezometric levels decreasing from NW to SE (CELICO, 1983): near the main tectonic features, the highly cataclased rocks cause major piezometric head losses, with permeability in the range of 10^{-8} m/s vs. 10^{-4}-10^{-7} m/s, i.e. the typical values of the fractured and karstified aquifer (MONJOIE, 1978). This process creates a "hydrostructural high" area in the northern sector of the massif, with preferential discharge towards North (Chiarino, Ruzzo, Rio Arno springs). However, through water seepage from or to neighbouring hydrogeological basins, the above area also supplies the springs located on the southern and eastern sides of the massif, at increasingly lower elevations (Tavo, L'Aquila Plain and Tirino springs); the latter springs also receive the contributions of shallower recharge areas. The final discharge area of the entire basal aquifer, whose flow has a dominant NW-SE direction, is represented by the Pescara springs, lying in the lowest point of the aquifer boundary (FIG. 1). Groundwater circulation is further complicated by dolomitic deposits at the base of the sedimentary sequence, whose permeability is lower (10^{-8}-10^{-9} m/s). Near the structural highs, these deposits may hinder groundwater circulation. Additionally, the fact that the carbonate sequence is interbedded with low-permeability layers (such as the "rosso ammonitico" and Oligo-Eocene marls) contributes to keeping the aquifer at high elevation and to creating perched groundwater. The latter, which give rise to numerous small springs (discharge of 0.1-5 l/s), have a total annual discharge of $50 \cdot 10^6$ m^3 (CELICO, 1983).

Given its scale and hydrodynamic properties, the Gran Sasso aquifer not only hosts massive permanent reserves but, under natural conditions, it can deliver about 25 m^3/s on average, feeding the springs on the northern face of the massif, those of the L'Aquila Plain, of the Tirino valley and of Popoli (TAB. 1).

In terms of chemical composition, the water from the springs is typically bicarbonate-alkali-earth (FIG. 2) and rich in calcium ions, as expected from a carbonate aquifer. The Tirino spring waters have a higher sulphate content, probably deriving from the evaporite-bearing dolomite bedrock. Electrical conductivity (and thus salinity) has a growing trend from the northern springs (200-300 µS/cm) to the basal springs of the Tirino valley and Capo Pescara (400-500 µS/cm), i.e. the final discharge area of the Gran Sasso groundwater. Poorly high conductivity values are observed in the the Tavo and L'Aquila plain springs (250 µS/cm), indicating recharge by fast-running groundwater in a karst environment.

One of the most important infrastructures of central Italy is represented by the Gran Sasso motor-way tunnels. At an elevation of about 970 m above sea level (a.s.l.), the tunnels connect the L'Aquila side of the massif (SW, Assergi) to its Teramo side (NE, Casale S. Nicola) (FIG. 1).

TAB.1 – Gran Sasso main springs, measured in 1994-2000 (mean discharge and electrical conductivity). Discharge data measured before motor-way tunnel construction, see CELICO (1983).

Spring	*Elevation (m a.s.l.)*	*Mean discharge (1994-2000) in m^3/s*	*Mean discharge before tunnel construction (m^3/s)*	*Electrical conductivity (µS/cm)*
Chiarino	1315	**0.05**	0.08	305
Rio Arno	1524	**0.19**	0.30	310
Gruppo Ruzzo	750-1660	**0.33**	0.57	300
Mortaio d'Angri	650	**0.14**	0.28	260
Vitella d'Oro	690	**0.18**	0.38	220
Vetoio	640	**0.44**	0.70	460
Boschetto	625	**0.22**	0.22	410
Tempera	650	**0.79**	1.20	240
Capo Vera	650	**0.19**	0.50	240
Capodacqua Tirino	340	**2.80**	5.00	500
Presciano	336	**1.95**	2.00	570
Basso Tirino	300	**5.50**	5.40	545
S.Calisto	300	**2.00**	1.80	560
Capo Pescara	270	**6.70**	7.50	530
Tunnel L'Aquila side	970	**0.45**	0	225
Tunnel Teramo side	970	**1.05**	0	225

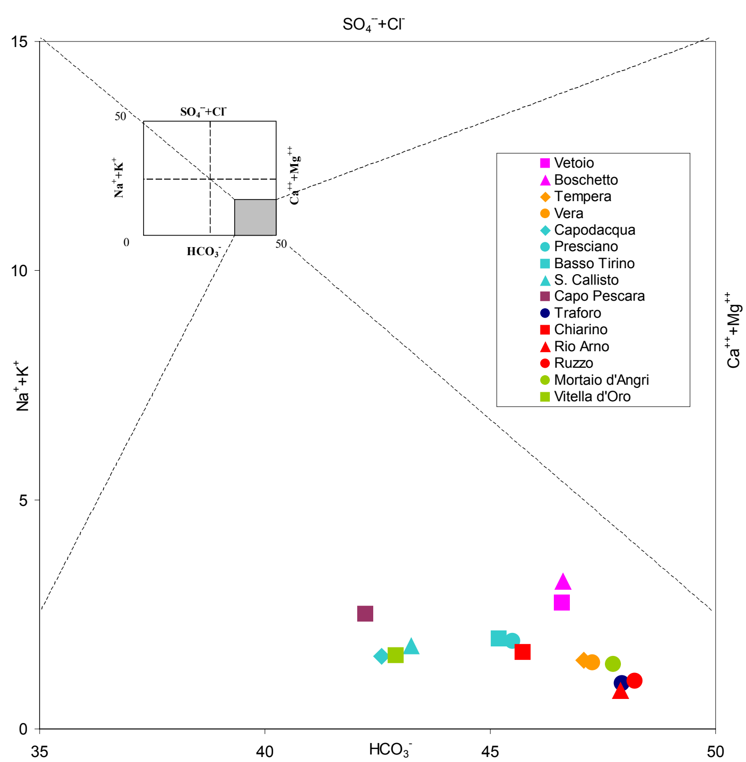

FIG. 2 – Hydrochemistry of the Gran Sasso springs illustrated by Chebotarev diagram. The values reported in the diagram refer to the January 2001 survey. Spring names refer to Table 1.

Gran Sasso Motor-Way Tunnels

The two parallel tunnels, built between 1969 and 1982, have a length of over 10 km, a mean cross-sectional area of 80 m^2 in carbonate rocks and of about 110 m^2 in the argillitic-marly deposits. The tunnels cross the northern portion of the Gran Sasso carbonate hydrogeological unit (CELICO, 1983; ADAMOLI, 1990).

The underground laboratories of INFN (Istituto Nazionale di Fisica Nucleare - National Nuclear Physics Laboratory) were placed beside the tunnels (on the left side, 6,250 km away from the motor-way exit to Assergi); construction works started in 1982 and ended in 1987. The laboratories have three experimental rooms connected by galleries and by-passes and an interferometric station consisting of three minor galleries with a triangular arrangement (FIG. 3).

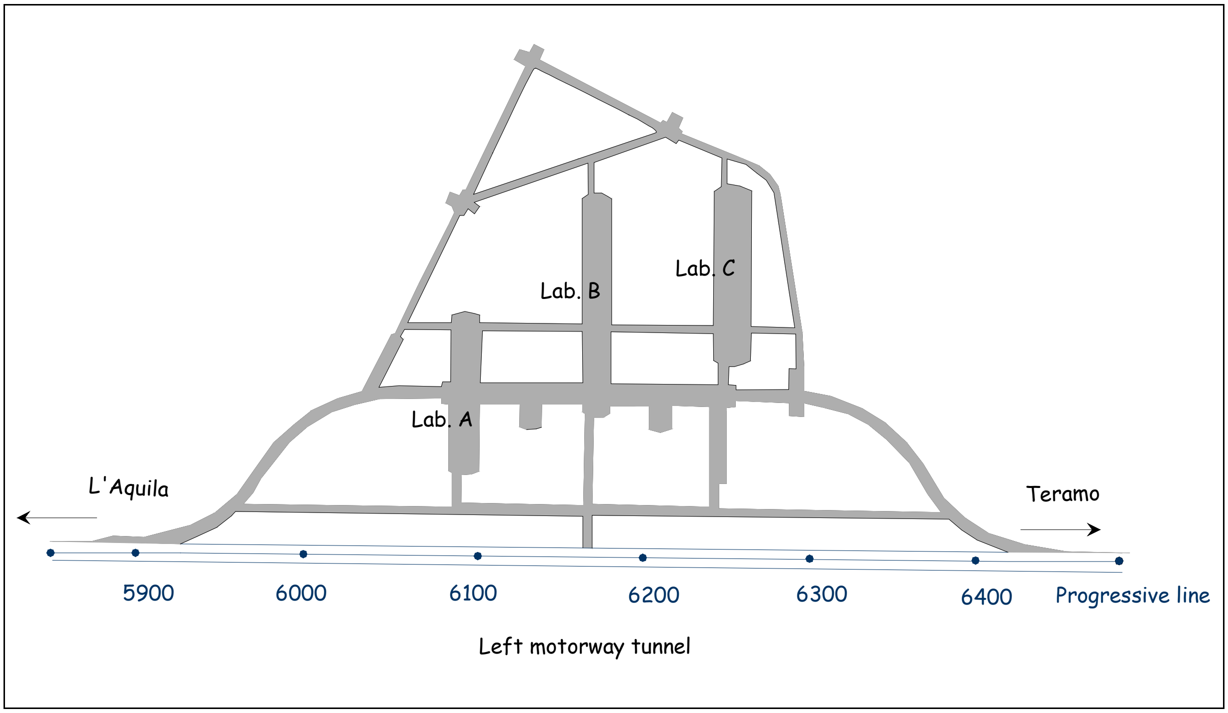

FIG. 3 – Laboratories and left motor-way layout. The progressive line shows the distance (in metres) from the motor-way exit to Assergi-L'Aquila (South side).

Studies for litho-stratigraphic and structural characterisation of the sector of the massif involved by the tunnels and INFN's laboratories confirmed the complex hydrogeological setting of the unit under study, emphasising the hydrogeological role of its tectonic unconformities (MONJOIE, 1975).

Surface geology surveys were carried out along the route of the motor-way (CALAMBERT *et alii*, 1972a; ADAMOLI *et alii*, 1982). From 1972 to 1974, after the start of excavations, three deep holes (Fontari, M. Aquila and Vaduccio) were bored on the vertical line of the tunnels (CALAMBERT *et alii*, 1972b) and underground surveys were made along the two tunnels (ANAS – COGEFAR, 1980; CATALANO *et alii*, 1986).

The three deep holes (Fontari, M. Aquila and Vaduccio) evidenced that, before excavations for the tunnels, the maximum elevation of the water table in the investigated sector (coinciding with the hydrostructural high) was about 1,600 m a.s.l., i.e. approximately 600 m above the tunnel plane (FIG. 4). A high-permeability karstified belt was found at an elevation of 1,500 to 1,700 m a.s.l.

The prevailing groundwater flowpaths – supported by tests with tracers (fluorescin) injected into the Fontari hole (MONJOIE, 1975; ANAS – COGEFAR, 1980) – are actually from NW to SE: the Apennine-trending joints and extensional faults create an actual groundwater discharge net.

The stratigraphic-structural and hydrogeological setting of the investigated unit (large potential discharge, faults with thick cataclastic belts, high water pressures) caused major problems upon and slowed down tunnel boring works.

Just think that, upon crossing of the Faglia di Valle Fredda fault (FIG. 4), sudden and massive in-rush of water (up to 20,000 l/s) occurred, which poured a significant amount of cataclastic material into the tunnel. Similar events happened during the crossing of the highly tectonised and jointed calcareous terms.

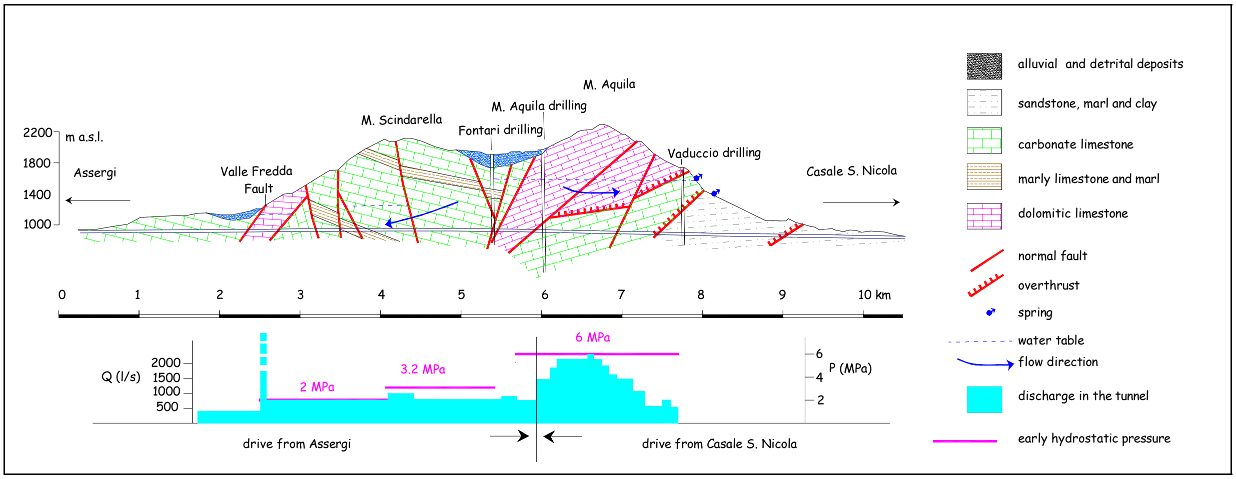

FIG. 4 – Underground mining versus discharge in the motor-way tunnel. The tunnel direction is showed in Fig. 1.

To operate under safety conditions, the natural drainage represented by the tunnels was complemented with well-points along the perimeter of the excavation. After lining of the tunnels, points of water drainage and exploitation were created around the tunnels and at the foot of the excavation, in order to ensure vault stability (ADAMOLI, 1990). The drainage water is exploited for drinking uses on the L'Aquila and Teramo sides of the massif.

Clearly, the motor-way tunnels permanently interfered with the hydrogeological equilibrium of the investigated area: their most significant effect is the lowering of the piezometric surface by about 600 m on the vertical line of the tunnels, with consequent groundwater drainage of some high-altitude springs and, in part, of those supplied by the basal aquifer (especially those closer to the tunnels).

Attention was focused on this particular aspect of the construction of the Gran Sasso tunnels already upon drilling. Discharges and the main physico-chemical and isotope parameters of the spring and tunnel waters were monitored for over five years; tracer and high-pressure tests were carried out (MONJOIE, 1975) to reconstruct the groundwater hydrodynamics of the carbonate massif in more detail and in particular of the sector involved by the tunnels.

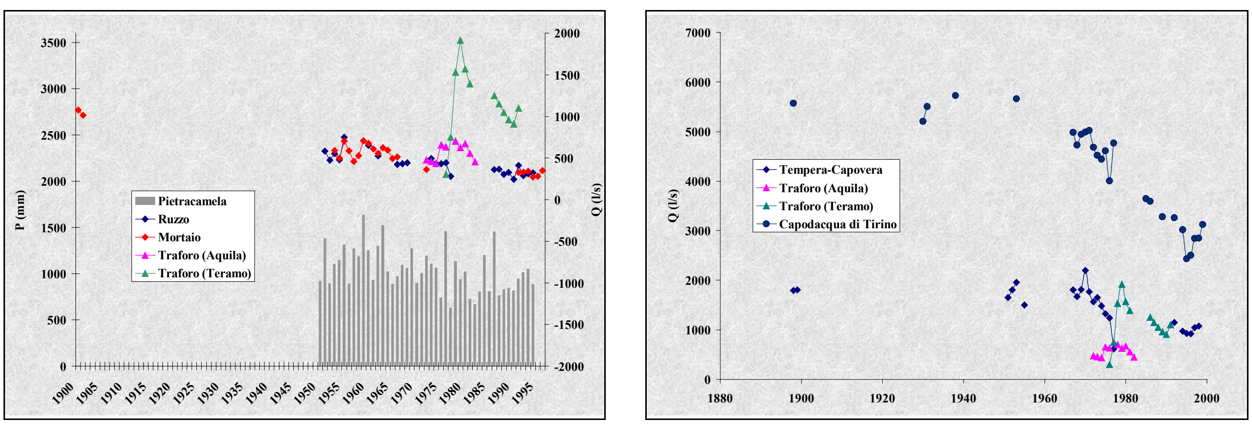

FIG. 5 – Discharge of springs located on the North (a) and South (b) mountain-side versus precipitation and discharge in the tunnel. Spring names refer to Table 1.

Similar studies (CELICO, 1978; CELICO, 1983; CELICO *et alii*, 1984; BONI *et alii*, 1986) were conducted for predicting the effects induced by tunnel excavation on the natural hydrogeological system.

The most immediate consequence was a decrease in the discharge of springs located on the northern side, especially those belonging to the Ruzzo group; the decrease was not related to the trend of precipitation (FIG. 5). Quantitative analysis of the waters drained by the tunnel (240 million m^3 from 1978 to 1981) demonstrated the transient depletion of the permanent water reserves stored in the aquifer.

When the "new" hydrogeological equilibrium was reached, the measured discharge in the tunnels was equal to roughly 1.5 m^3/s.

The consequences of tunnel drainage on spring discharge (on both the northern and southern sides) were estimated on the basis of the analysis of isotope data (oxygen-18, deuterium, tritium) of the waters from the main springs and the tunnels, monitored from 1970 to 1982 (CELICO *et alii*, 1984). The key findings from such study can be summarised as follows:

- the waters from the northern springs (Chiarino, Rio Arno, Ruzzo group) had the same isotope composition as the tunnel waters. Consequently, they were likely to be more affected by tunnel drainage;
- a sharp decrease in the discharges from the Vitella d'Oro and Mortaio d'Angri springs was regarded as unlikely: their waters had stable isotope composition, slightly but significantly different from the one of the tunnel waters;
- the decrease in the discharges from the south-eastern springs (Presciano, Capo d'Acqua di Tirino, Bussi, San Calisto, Capo Pescara) was considered to be negligible, since the isotope composition of their waters was definitely different from the one of the water drained by the tunnel and thus suggestive of a different recharge area, i.e. of a different groundwater origin and dynamics. The waters coming from the north-eastern sector of the massif were thus assumed to be highly diluted with waters infiltrating into a different and limited recharge area.

The above predictions are corroborated by subsequent observations and investigations, focused on the southern springs and aimed at determining the role of the Gran Sasso motor-way tunnel drainage in groundwater hydrodynamics (FARRONI *et alii*, 1999; MASSOLI NOVELLI *et alii*, 1997; MASSOLI NOVELLI & PETITTA, 1998; PETITTA & MASSOLI-NOVELLI, 1998; PETITTA & TALLINI, 2002).

Current Situation

After completion of the underground structures in the 1990s, the Consorzio di Ricerca del Gran Sasso (Gran Sasso Research Consortium) was established. The Consortium, including local governments and research institutions, had among others the task of collecting environmental data on the Gran Sasso area, designated as National Park in 1991. In the Consortium's activities, hydrogeological investigations, conducted for different purposes and by different work groups (STIGLIANO *et alii*, 1999; PETITTA & TALLINI, 2002), played a leading role. These investigations were targeted to monitor spring discharge and thus assess the impact of tunnel drainage on water supply and groundwater circulation. Conventional approaches (survey of springs and water points, monitoring of spring and stream discharges, physico-chemical characterisation of waters) were associated with chemical and stable isotope ($\delta^{18}O$‰, $\delta^{2}H$‰, $^{87}Sr/^{86}Sr$) analyses of spring waters (PETITTA & TALLINI, 2002; BARBIERI *et alii*, 2005).

The investigations were focussed on specific sectors of the massif, i.e. on the discharge areas of groundwater, especially on the southern slope of the massif, which includes the L'Aquila plain, the Tirino valley, the Popoli springs and the middle reach of the Aterno River. The discharge measurements displayed a generalised drop in spring discharge vs. the values recorded immediately after construction of the tunnels.

The southern springs, which delivered about 2 m^3/s in the past, do not reach 1 m^3/s at present and, as they are almost completely tapped, their waters are hardly monitorable. The springs of the L'Aquila sector have a total discharge of approximately 1.6 m^3/s, of which about 1 m^3/s from the Vera group (stable discharge with minimum seasonal fluctuations) and about 0.6 m^3/s from the group of the L'Aquila plain (whose discharge has significant seasonal variability, Table 1). The Vera group of springs had an over 40% decline in its discharge vs. pre-tunnel values (1 m^3/s vs. 1.7 m^3/s), whereas the springs of the L'Aquila plain (Vetoio and Boschetto) had an about 30% drop (0.66 m^3/s vs. 0.92 m^3/s) (FIG. 5, TAB. 1).

Among the Tirino valley springs, the Capodacqua spring, which lies at higher elevation, shows significantly variable discharge values, definitely lower than pre-tunnel ones (about 3 m^3/s as compared to about 5 m^3/s in the past, i.e. down by 40%). The Presciano and Lower Tirino valley springs have a more stable discharge and do not show significant decreases with respect to their historical values. The S. Calisto and Capo Pescara springs, in the Popoli area, have also a minimum decrease vs. pre-tunnel values.

The current discharges from the southern springs amount to approximately 21 m^3/s, of which about 7 from the Capo Pescara spring. All springs have recorded a clear and progressive increase in their discharges since the Autumn of 1996, whereas the discharges in the 1994-1996 period were always lower.

To complete the investigations on spring discharges, the main streams of the area (Aterno and Tirino) were monitored. This activity showed a relationship between surface water and groundwater. In crossing the L'Aquila plain, the Aterno River significantly interacts with the multi-layer aquifer of the Quaternary deposits, which is in turn fed by the nearby south-western border of Gran Sasso. In particular, the actual increase in in-stream discharge is on average equal to 0.15 m^3/s, as against 0.4 m^3/s reported in the literature (CELICO, 1983) during tunnel construction. Investigations on the Tirino River showed the contributions of streambed springs in addition to the main ones; the mean value of such increase (roughly 0.7 m^3/s) validates past estimations.

The hydrogeological picture resulting from the data summarised above compares with the natural situation preceding the construction of the tunnel, which is well documented hydrogeologically. Unfortunately, in the subsequent period (1985-94), the monitoring activity was almost completed discontinued, causing an information gap which coincided with the transient period induced by tunnel drainage.

In effect, the Gran Sasso aquifer is supposed to have responded in two ways to tunnel excavation and interception of its groundwater: in the initial stage, by discharging huge volumes of water and depleting its permanent reserves (discharge of several m^3/s); and, in the subsequent stage, under "constant head conditions", by lowering the piezometric surface with a 600 m drawdown (ADAMOLI, 1990). At a later stage, the aquifer is likely to have attained a new hydrodynamic equilibrium, which was no longer natural but forced by tunnel drainage. The achievement of this new steady state is confirmed by the recent increase in spring discharge, which was observed after 1996 thanks to an increase in meteoric water inflow and thus in aquifer recharge.

Post-tunnel monitoring of the Gran Sasso springs shows that the overall decline in spring discharge is by far higher than tunnel drainage, which currently ranges between 1.3 and 1.5 m^3/s, as predicted. This situation may be justified by the likely concurrent decrease in meteoric waters and thus in aquifer recharge. As a matter of fact, in the late 1980s and early 1990s, there was a period of drought with heavy consequences on the discharges from all the springs of the central Apennines (PRESIDENZA CONSIGLIO MINISTRI, 1994). Moreover, recent studies on climate indicate variations in the annual distribution of precipitation in the last century (DRAGONI, 1998), associated with temperature increases. This assumption is sustained by the separate examination (FIG. 6) of precipitation on the massif in the Winter period (October-March) and in the Summer period (April-September): seasonal precipitation vs. annual precipitation fell almost exclusively in the Winter period (November-April), with consequent direct effects on aquifer recharge.

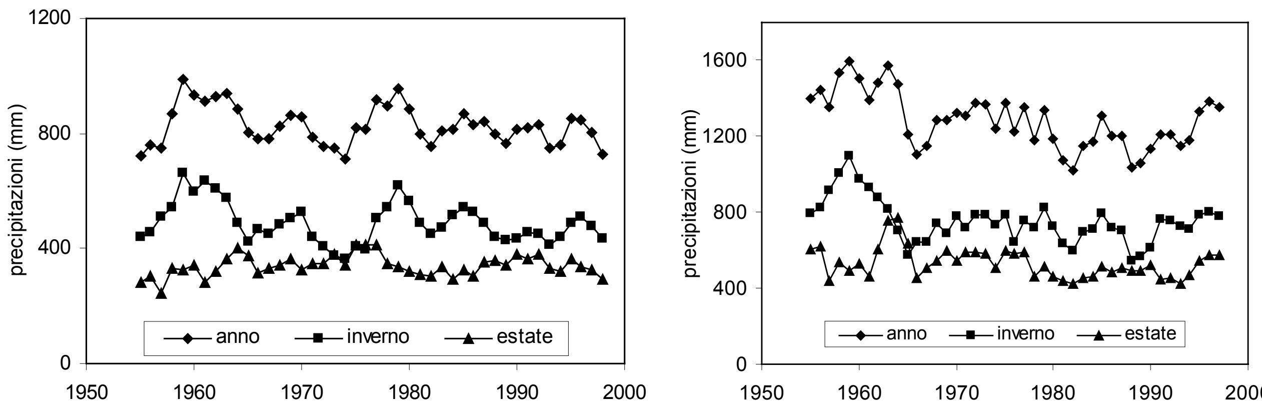

FIG. 6 – 3-year moving average of rainfall data (yearly, Winter and Summer values). Average calculated from data collected in some precipitation monitoring stations located on the Gran Sasso, southern side (left) and northern side (right). The rain stations are Castel del Monte, Termine, Montereale, L'Aquila, Capestrano, Pietracamela, Nerito, Fano a Corno, Isola del Gran Sasso.

Hydrochemical and isotope investigations not only validated the conceptual hydrogeological model, but also the role that the motor-way tunnels play in the interception of groundwater flowing predominantly towards the northern springs and, to a lesser extent, towards the southern springs. In particular, the tunnel water has an extremely low hydraulic conductivity (about 200 µS/cm), suggesting interception with direct recharge water, which is likely to circulate in pre-tunnel- identified karst horizons (MONJOIE, 1980). The results of isotope analyses are consistent with those from previous analyses (CELICO *et alii*, 1984), confirming that groundwater circulation in the hydrogeological system was disturbed above all in the immediate vicinity of the tunnel drains. $^{18}O/^{16}O$ ratios infer recharge from more elevated mean elevations for the northern springs vs. the southern ones and, consequently, the likely common origin of the waters intercepted by the tunnels and of those discharged by the northern springs.

Impact of the New Structures

For over one decade, a hot debate has been taking place on the project of enlargement of INFN's laboratories and construction of a third tunnel of access and service to the same laboratories (project approved by law no. 366 of 29 November 1990). The about 6 km-long new tunnel is planned above the two existing tunnels; the new laboratories, instead, will be placed in the proximity of the present ones.

Now, multiple basin-scale and detailed investigations have been conducted so far on the Gran Sasso carbonate massif (and on the sector involved by the new excavations). The wealth of data produced by these investigations makes it possible to make reliable predictions on the effects of the above underground structures on the local hydrodynamic conditions.

The analysis of the main issues related to the prediction of the interactions between the planned underground structures and the local hydrogeological setting may be summarised as follows:

- the third tunnel will almost entirely extend above the present tunnels and will thus largely involve a portion of the aquifer which is now unsaturated (i.e. without groundwater) (FIG. 7);
- this portion of the aquifer is certainly unsaturated,

because the water table has long receded to the drainage level coinciding with the drains of the existing tunnels;

- the above assumption was tested by boring 14 holes above the level of the existing drains lying at the bottom of the motor-way tunnels; the holes did not intercept water, except for a minimum flow of waters deriving from seepage into the unsaturated medium. Had these waters continued their natural downward flow, they would have reached their present discharge area, i.e. the drains of the existing tunnels (lying a few meters below);
- the lowering of the water table to the level of the motor-way tunnel drainage was also demonstrated by existing piezometers, which confirmed that the new service tunnel would be bored into rocks drained as far as 5,100 m away from the motor-way exit to Assergi;
- the new laboratories will instead be built in an assuredly saturated area of the aquifer (near the local discharge area of the aquifer, represented by the existing structures); this assumption was validated by 6 boreholes;
- this area, however, has a weak piezometric head (typical of carbonate aquifers), even near the groundwater discharge area. For the past 7 years, this piezometric head has practically remained unchanged;
- the new laboratories (and, to a lesser extent, the section of the tunnel which will be located inside the aquifer) will certainly drain the aquifer. However, the intercepted waters will account for only a fraction of the water presently drained by the nearby existing infrastructures. It will suffice to consider that, although the existing piezometers recorded drainage of about 10-20 l/s, this amount has not changed the total drainage by the present laboratories. At any rate, the new laboratories may be located in a different position, to avoid interferences with the aquifer, although this precaution is useless.

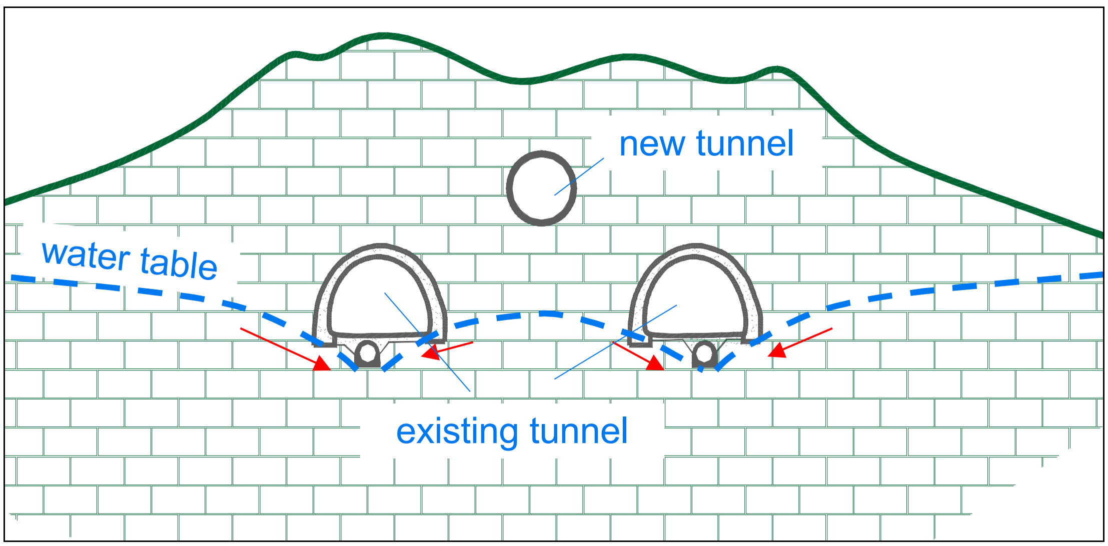

FIG. 7 – Hydrogeological scheme (not in scale) of the existing motor-way tunnels and of the new tunnel. Red arrows show drainage by the existing tunnels.

In conclusion, the construction of the third tunnel and of the new INFN's laboratories in the Gran Sasso massif - in their planned configuration – is feasible and will not unbalance local groundwater circulation. Indeed, even considering the substantial modification that the two tunnels caused to the hydrogeological system, the new structures cannot further alter the current hydrodynamic equilibrium.

It is always difficult to fully characterise a hydrogeological system, because there are always some missing links: some aspects remaining to be assessed, some portions of the aquifer to be investigated, some phenomena to be analysed in more detail, both spatially and temporally. Nonetheless, in the case under review, the available hydrogeological knowledge is such as to validate the feasibility and safety of the new underground structures. Furthermore, no tunnel planning has benefited to date from such a wealth of data; in particular, the data obtained from prior construction of two side-by-side tunnels, extending parallel to the newly planned tunnel and acting as sub-horizontal test holes, are particularly valuable.

References

ADAMOLI L. (1990) - *Idrogeologia del massiccio carbonatico del Gran Sasso e conseguenze idrogeologiche degli scavi autostradali.* Geologia Tecnica, 3, 4-15.

ADAMOLI L. BERTINI T., CHIOCCHINI M., DEIANA G., MANCINELLI A., PIERUCCINI U., ROMANO A. (1982) – *Ricerche geologiche sul Gran Sasso d'Italia (Abruzzo).* Studi geologici Camerti, VII.

ALLOCCA V., CELICO P., FABBROCINO S. (2003) – *Grandi gallerie in realtà idrogeologiche complesse*. Atti 1° Congresso Nazionale AIGA, Febbraio 2003, Chieti, 19-30.

ANAS-COGEFAR (1980) - *Gran Sasso, il traforo autostradale.* Ed. Grafiche Sefra, Milano.

BARBIERI M., BOSCHETTI T., PETITTA M., TALLINI M. (2005) - *Stable isotope (^2H, ^{18}O and $^{87}Sr/^{86}Sr$) and hydrochemistry monitoring for groundwater hydrodynamics analysis in a karst aquifer (Gran Sasso, central Italy). Applied Geochemistry*, in press

BIGI S., CALAMITA F., CENTAMORE E., DEIANA G., RIDOLFI M., SALVUCCI R. (1991) – *Assetto strutturale e cronologia della deformazione della zona d'incontro tra le aree umbro-marchigiana e laziale-abruzzese (Marche meridionali e Lazio-Abruzzo settentrionali).* Studi Geologici Camerti, vol. spec. 1991/2.

BONI C., BONO P., CAPELLI G. (1986) – *Contributo all'idrogeologia dell'Italia Centrale: analisi critica dei metodi di ricerca.* Mem. Soc. Geol. It., 35.

CALAMBERT L., CATALANO P:G:, CONATO V., LAMBRECHT L., MONJOIE A. (1972 (a)) – *Observations dans le massif du Gran Sasso (Apennin central).* C.R. Acad. Sc. Paris, 274.

CALAMBERT L., CATALANO P:G:, CONATO V., LAMBRECHT L., MONJOIE A. (1972 (b)) – *Le sondage de Fontari dans le massif du Gran Sasso (Apennin central).* C.R. Acad. Sc. Paris, 274.

CATALANO P.G., CAVINATO G.P., SALVINI F. & TOZZI M. (1986) - *Analisi strutturale nei laboratori dell'I.N.F.N. del Gran Sasso d'Italia.* Mem. Soc. Geol. It., 35, 647-655.

CELICO P. (1979) – *Schema idrogeologico dell'Appennino carbonatico centro-meridionale.* Memorie e Note dell'Ist. Di Geol. Appl., 14, 1-97.

CELICO P. (1983) - *Idrogeologia dei massicci carbonatici, delle piane quaternarie e delle aree vulcaniche dell'Italia centro-meridionale: Progetti speciali per gli schemi idrici nel Mezzogiorno.* Quad. Cassa Mezzog., 4/2, 1-225.

CELICO P., GONFIANTINI R., KOIZUMI M., MANGANO F. (1984) – *Environmental isotope studies of limestone aquifers in central Italy.* Int. Atomic Energy Agency, Vienna.

DRAGONI W. (1998) – *Some considerations on climatic changes, water resources and water need in the Italian region south of the 43°N.* In: Issar S. & Brown N. Eds., Water, environment and society in times of climatic change, 241-271. Kluiwer.

FARRONI A., PETITTA M., TALLINI M. & TOGNA A. (1999) - *Indagine sull'Idrogeologia del Massiccio del Gran Sasso. Revisione dei dati esistenti e nuove considerazioni.* Studi Geologici Camerti, Vol. Spec. 1999, 117-135.

GHISETTI F., VEZZANI L. (1983) – *Deformazioni pellicolari mioceniche e plioceniche nei domini strutturali esterni dell'Appennino centro-meridionale (Maiella ed arco Morrone Gran Sasso).* Mem. Soc. Geol. It., 26.

MASSOLI-NOVELLI R., PETITTA M. (1997) - *Hydrogeological impact of the Gran Sasso tunnels (Abruzzi, Italy).* Proceedings International Symposium on Engineering Geology and the Environment, Athens, Greece, 23-27 June 1997, vol.3.

MASSOLI-NOVELLI R., PETITTA M. (1998) - *Le sorgenti del Vera e di Capodacqua Tirino (L'Aquila): caratteristiche ed uso della risorsa*. Atti Seminario "Le nuove sorgenti", Parco Nazionale d'Abruzzo, 29-30 marzo 1996.

MONJOIE A. (1975) - *Hydrogeologie du massif du Gran Sasso (Apennin central).* Coll. Pubbl. Fac. Scienze Appl. Univ., 53, 1-60, Liegi.

MONJOIE A. (1978) - *Problèmes hydrogèologiques rencontrès par les tunnels autoroutiers dans le massif calcaire du Gran Sasso (Appenin central).* Symposium I.H.E.S. "Implications de l'Hydrogèologie dans les autres Sciences de la Terre", Memoire hors série CERGH-USTL, Montpellier, 287-298.

MONJOIE A. (1980) - *Prévision et contròle des caractéristiques hydrogéologiques dans les tunnels du Gran Sasso (Appenin, Italie).* Livre Jubilaire, L. Calembert, 209-229. Ed. Thone, Liège.

PETITTA M., TALLINI M. (2002) – *Idrodinamica sotterranea del massiccio del Gran Sasso (Abruzzo): nuove indagini idrologiche, idrogeologiche e idrochimiche (1994-2001).* Boll. Soc. Geol. It., 121, 343-363.

PETITTA M., MASSOLI-NOVELLI R. (1998) - *Tirino Springs (Abruzzi, Italy): an important groundwater resource for humans and environment*. Proceedings XXVIII International Congress AIH, Gambling with groundwater, Las Vegas, USA, 28 Sept - 2 Octob 1998.

PRESIDENZA DEL CONSIGLIO DEI MINISTRI (1994) – *La siccità in Italia, 1988-1990.* Dipartimento Protezione Civile. Ufficio Coordinamento delle attività di previsione e prevenzione, Servizio rischio idrogeologico, Roma, Istituto Poligrafico e Zecca dello stato, 1-193.

SCOZZAFAVA M. & TALLINI M. (2000) – *Vulnerability of the carbonatic aquifers with SINTACS Method: The case-study of the Gran Sasso Massif (Central Italy).* Enne G., Zanolla C. & Peter D. Eds., Desertification in Europe: mitigation strategies, land use and planning, 463-472. EUR 19390, Luxembourgh.

STIGLIANO P., ALTIERI A., BARBERI R., DE CATERINI G., MASSOLI-NOVELLI R., MICCADEI E., PIACENTINI T., PETITTA M. & SALVATI R. (1999) - *Studi per un monitoraggio idrologico del massiccio del Gran Sasso (Abruzzo).* Studi Geologici Camerti, vol.spec. 1999, 153-170.

VEZZANI L. & GHISETTI F. (1998) - *Carta geologica dell'Abruzzo*, scale 1:100,000. S.EL.CA., Firenze.