DEVELOPMENT OF HUMAN ACTIVITIES IN THE UNDERGROUND SPACE AND GROUNDWATER PROTECTION

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SUMMARY: The utilization of the underground space for carrying out human activities goes far back into antiquity. A review of underground space major uses over time is given and pros and cons relating to the huge increase in tunnelling are listed. The impact on groundwater resources is estimated. And significant variations in the aquifer regulation and storage capacity volume, hydraulic conductivity and transmissivity, water flow and energy velocity are discussed.

1. UTILIZATION OF THE UNDERGROUND SPACE OVER TIME

The utilization of the underground space for carrying out human activities goes far back into antiquity, the earliest tunnels being caverns and man-made cave dwellings and galleries. Far from exhaustively and systematically reviewing all possible uses of the underground space over time, this article illustrates a few representative and poorly known cases.

The multi-millennian history of the use of sub-surface cavities started out in the Neolithic age when the underground space served as hiding place to man.

The underground chambers of Agrigento, the ancient Greek city of Acragas, were a major hydraulic engineering achievement. Fully excavated within the rock and designed for water collection (Arnone, 1991; Polemio, 1995) they date back, according to Arnone, to as early as 480 BC. This date is most likely to refer to the final completion of the work that had started many years earlier. Underground chambers were a sort of aqueduct serving up to 200,000 people and they undoubtedly contributed to the economic and social development of the most flourishing city of Graecia Magna (Fig. 1).

A system of wells, underground passages (*leads* or narrow galleries) and reservoirs, quarried in a soft calcarenitic aquifer, ran along the sides of the Valley of Temples at various depths below ground level (not exceeding 30 metres) overlying a clay layer. The underground chambers were located where abundant water veins outflowed between the calcarenite and the underlying clay. From these points, serving as water-collection works, passages branched out ending at the anciently inhabited citadel.

Leads, chambers and pillars show highly developed excavation skills, solid rock being cut through by pickaxes. Round-shaped wells can still be found at a regular distance along the galleries, corresponding to curves and branches. A staircase is excavated within the rock in every well (Fig. 2).

At a later period, the name catacomb came to be given to subterranean passages used by the early as secret meeting places for worship in times of Roman empire persecution. The Christians, as well, built also the underground city of Kaymakli (Turkey), on ten sub-surface storeys to accomodate thousands of people, to avoid Muslims persecution.

Throughout the 16th century, the well-off élite made extensive use of underground chambers to find relief from hot weather. In Palermo's villas the underground space was used in summertime during hot sirocco days (Di Cristofalo et al., 1989). The so-called "sirocco rooms" were a system of interconnected underground chambers and passageways. The chambers had shafts to provide light. Their shape ensured air cooling by convection along the rock walls and by water evaporation from

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fountains. Paintings, frescos, sculptures and plants made underground chambers more attractive and pleasant. In addition, these highly ventilated rooms were sometimes large enough for parties to be held.

In Eastern countries, as well, the utilization of the underground space has spurred the development of human activities. In India, the underground was a largely developed natural resource and subterranean cavities had been excavated within the loess since the Neolithic age (Sharma and Bhandari, 1989). Later on, underground rooms were built beneath castles, palaces and places of worship to accommodate warehouses and water storage, to lodge elephants and other animals and serve as summertime cool apartments or burial ground.

1.1 Recent boost to underground space use

During the last century, railroad led to a tremendous expansion in tunnelling techniques for civil-engineering projects. Nowadays a number of underground constructions have been made to preserve the scenic environment (i.e. the Lecco-Trivio expressway in the vicinity of Como Lake), to alleviate

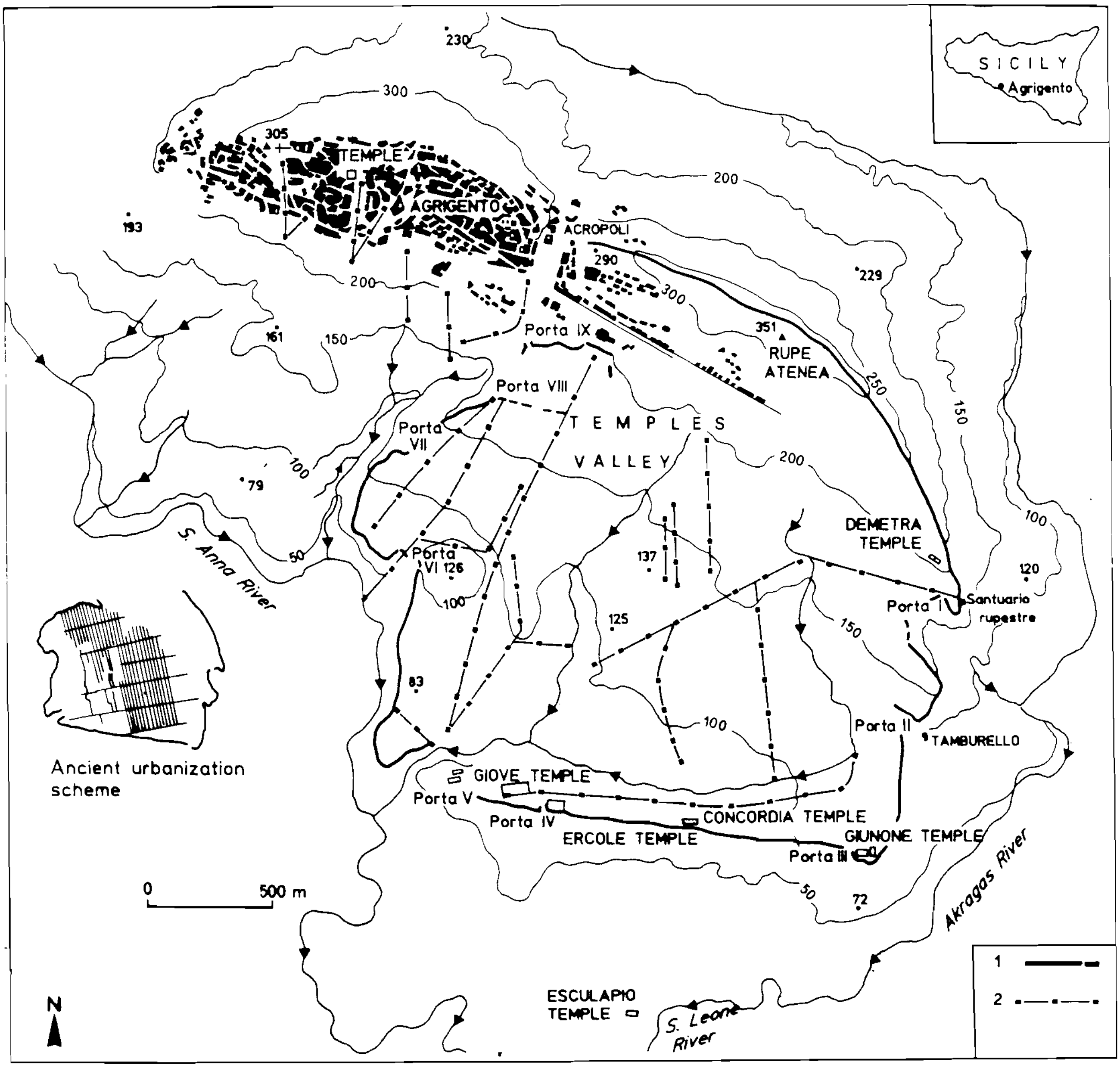

Fig. 1 - Map of Agrigento's underground chambers in the Temples Valley: 1) ancient city walls; 2) aqueduct galleries (Adapted from IGM, 1957).

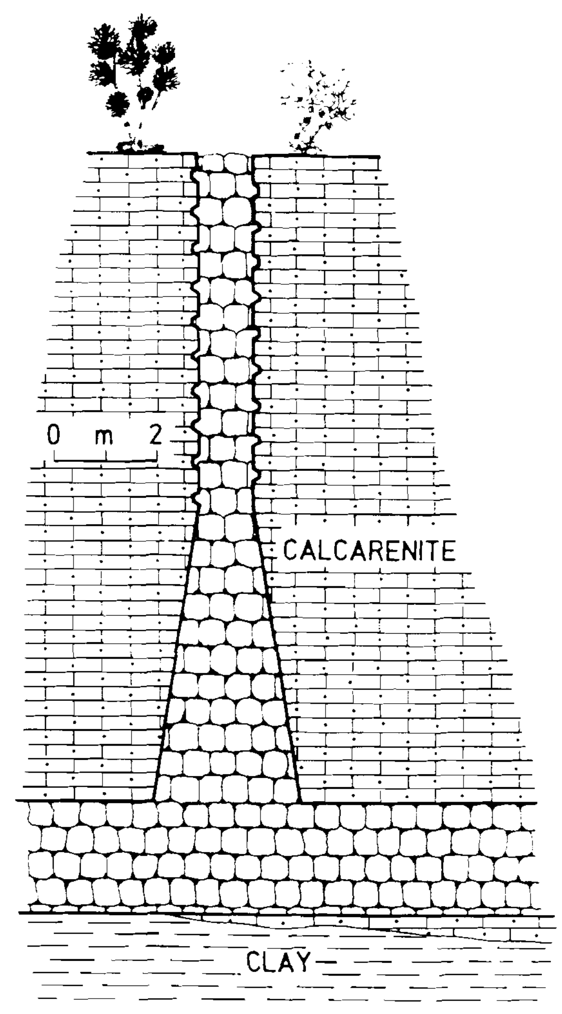

Fig. 2 - Agrigento's underground chamber well.

surface traffic congestion or to increase high-risk plant safety, to optimize transport facilities and provide viable alternatives to sea routes to the islands (the English Channel Tunnel and the Seikan Tunnel in Japan) (Pelizza, 1988; Cotecchia, 1993).

In Shanghai alone, over ten years, more than 2,000,000 square metres of underground space have been devoted to the placement of shopping malls, parking facilities, hospitals, restaurants, theatres, hotels, subways and power plants (Polemio, 1993).

Underground settling provides protection against both natural and man-made risks, the soil acting as a strong barrier against a number of disturbance factors, such as: odours, vibrations, explosions and radiations. Also, the underground space preserves against industrial or war-time related pollution and may serve to accommodate warehouses and strategic installations. Furthermore, the underground low conductivity and high thermal inertia permit energy savings.

Given the wide range of applications, the underground space is likely to receive further consideration as a new land use system (Pelizza, 1988).

The overriding deterrent, however, remains human rooted fear of exploiting such space along with the need to investigate the impact of these structures on groundwater.

2. EFFECTS OF UNDERGROUND WORKS ON GROUNDWATER

Major drawbacks on groundwater quality, supply and use can be ascribed to underground work construction requirements. Water saturates the medium to be excavated resulting in thrusts on the lining and overall complications to construction operations. Hence, it is common practice to drain the aquifer prior to opening the subterranean cavity and dewater the rock mass around the estimated cavity. New boundary conditions are established which considerably modify the flow pattern in the portion of aquifer involved in the underground work.

Most underground excavations have encountered problems with water inflows. They may consist of continual dripping of water or up to thousand litres of water flow per second. (The Mount Bianco tunnel (0.8 m^3/s), the Gran Sasso tunnel (2.2 m^3/s) (Adamoli, 1989) and the S. Lucia railroad tunnel (1.5 m^3/s) (Celico et al., 1977).

Technical know-how, surveys and designing are generally focused on cutting flow rates to a minimum and dissipate water in the most economical way in order to prevent operational slowdowns in the work (Di Molfetta, 1991).

Thorough hydrogeological analysis is essential to assess the water resource capture covered by the layout. Attempts to quantify it may prove difficult, though, mainly where fissuring permeable rocks are found, water distribution being heterogeneous and anisotropic.

Italian experience shows that tunnel designs are rarely supported by parallel protection projects or underground drained water use projects.

An exception to the rule is the Abatemarco-Mezzafiumina water-conveyance tunnel, connected to Cosenza's water supply networks (Cotecchia et al., 1983). Preliminary investigations carried out prior to planning have enabled to predict the presence of a huge water table and design a collection and regulation work, thus permitting groundwater rational use, according to the hydrogeological flow rate of the drained aquifer. The tunnel, some 6.3 Km in length, had been specially designed to carry water from Favata and Nascejume springs to Cosenza (0.15 m^3/s). Along the way, the tunnel was intersected by an aquifer. The crossing was achieved by means of a draining section closed both upstream and downstream by impermeable screens. The aquifer, kept under pressure by the impermeable screens, was tapped when summer users called for higher flow rates. Peak water supply was therefore more than doubled, approaching some 0.4 m^3/s.

2.1 Reduction in regulation and storage capacity volume and decrease in transmissivity

Just like a dam where the crest level is reduced by lowering the spillway level, a tunnel designed to drain the surrounding aquifer calls for a fixed piezometric head, lower than the free elevation or the one naturally existing prior to excavation, for the aquifer volume to be reduced. The storage capacity accounts for the regulation and capacity volume of the underground reservoir. Hence, given the same recharge rate, spring outflows and drained discharges remain constant during the hydrological cycle, while their distribution is bound to vary and their use sometimes hampered. The Gran Sasso case provides a useful example: the peak elevation of the saturated aquifer inevitably lost for water storage because of the execution of the tunnel reaches about 650 m (Adamoli, 1989). It corresponds to the cross section of an indefinite area which will gradually expand until new dynamic balance conditions are created in the groundwater circulation.

Another example is provided by the St. Lucia railroad tunnel that, being located some 100 m below the permeability threshold bounding the aquifer, has resulted in an irreversible piezometric head decrease. A phenomenon which has made the Cava dei Tirreni Municipality well field improductive (Celico et al., 1977).

The aquifer lowering, due to water table-induced saturation or, broadly speaking, the reduction in the hydraulic pressure corresponds to a proportional reduction in hydraulic transmissivity.

2.2 Increase in water flow velocity and vulnerability

The construction of any underground work sunk in a water table requires drainage, as the work alters the aquifer boundary conditions. The tunnel provides an extremely rapid flow path along which water is drained away. The phenomenon could be quantified by calculating the mean velocity at which the water volume unit infiltrates into and outflows from the aquifer, according to the whole hydrological cycle. As far as quality goes, it is common knowledge that the increase in the mean velocity of water inflow/outflow from the aquifer results in a proportional decrease in the residence time, which is a drawback. It does not improve drained water quality, the purifying action of surface and sub-surface water flow being reduced.

The Gran Sasso highway tunnel and the St. Lucia railroad tunnel are good examples of increasingly low residence-time drained water, showing a clear-cut preference for artificially-induced groundwater flow.

When either poorly designed or maintained, underground chambers may help the seepage of polluting substances released by vehicles and industrial plants or introduced during the construction process by injections of coating and solidifying chemical grouts. A risk which is enhanced by the considerable penetration of the underground space into the aquifers.

Both residence time reductions and new pollution ways highly increase the aquifer vulnerability.

2.3 Drainage and transient flow

According to the hydrogeological time scale, underground drainage works immediately disturb the aquifer dynamic balance conditions.

The new boundary condition thriggers the transient stage, the duration of which depends on the aquifer nature and shape and on the type of construction work. After a time lapse comparable to the life of the work itself, the transient stage brings in a new equilibrium. The effects of water table drainage are increased accordingly, though at a slower rate, while artificially drained discharge rates are decreased.

It follows that preliminary knowledge of aquifer and water flow is crucial for preserving huge and precious groundwater. And numerical simulations should be made of the underground work impact, in order to predict the magnitude of drainage-related effects.

The paramount importance of this stage has been confirmed by the unanticipated discharges drained from the Gran Sasso tunnel, which have fed specially built or supplemented aqueducts. However, these discharges have been subject to a progressive decrease over the past years (Fig. 3), which has raised fears about water availability to the served networks in the next future.

2.4 Reduction in groundwater energy

The drainage-induced piezometric head partial reduction lessens the groundwater potential energy. The phenomenon does not always have a rapid and direct impact on groundwater circulation and spring regimen, mostly when the aquifer exhibits a complexe geological configuration. Therefore every single case has to be individually analysed and the possibility of drawback onset over time cannot be ruled out.

The reduction in potential energy is particularly severe when the water table is under pressure and made readily available by water-collection works, exploiting this peculiar circumstance.

The collection work of the Torbido spring water (Cotecchia et al., 1993) is a significant case. The wrong assessment of the spring hydrogeological pattern, conditioned by a sequence of tectonic events, had led to design a water-collection work consisting of a subhorizontal surface draining tunnel. A "modest" and "useful" potential energy reduction in the groundwater system was likely to occur. An effect which could, by no means, be regulated. After investigating the peculiar hydrogeological conditions, Authors suggested to proceed to the Torbido spring water collection through artesian wells. This solution has enabled to collect spring water by exploiting all available potential energy (the pressure head, which exceeded some thirty-meter water height versus ground level, being used instead of a pumping system) and adjust the drained discharge rate to demand.

Another example is provided by the Monpantero tunnel, in the Susa-Rivoli stretch of the Fréjus

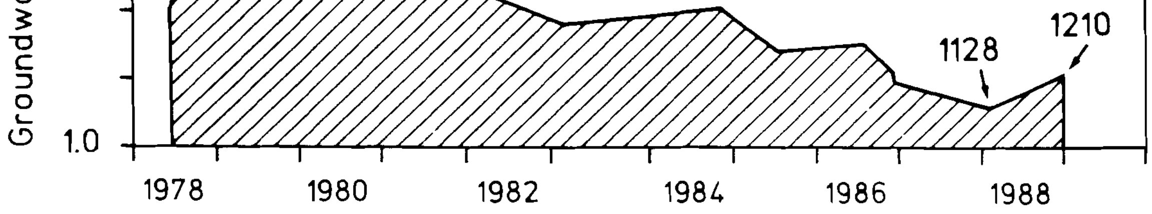

Fig. 3 - Water discharge rate (m3/s) drained from the Gran Sasso tunnel (Adamoli, 1989).

Highway (Pelizza et al., 1991). The collection of a formation made up of pebbles and assorted-size gravels found in a silty-sandy matrix, has resulted in abundant water inflows. On the surface, the Fontana Maria spring, which was the main water supply source of both Monpantero Municipality and Rio Gendola, was depleted. This event clearly shows that the dynamic balance between surface and underground waters is a complex phenomenon, often suffering from the potential energy variation of groundwater, stream, lake and/or sea.

2.5 Piezometric head lowering resulting in injury to the flora, fauna and landscape

The piezometric head lowering due to underground construction works may damage the flora when the upper part of the water table involved in the works affects soil humidity. The injury to the flora is irreparable. It leads to the loss of the existing plant cover. A low growth of other forms of plant life more suitable to the new conditions is likely to occur.

If the drained water table is used to irrigate crops or parks and gardens by means of wells, the effect is even more severe, given the economical complications deriving from the capacity loss of water-collection works.

In both cases, the fauna is likely to be endangered and the landscape modified.

An interesting case was studied by Fukuoka (1977) by means of infrared thermal remote-sensing. Tunnelling works were increasingly injuring the local flora (Fig.4).

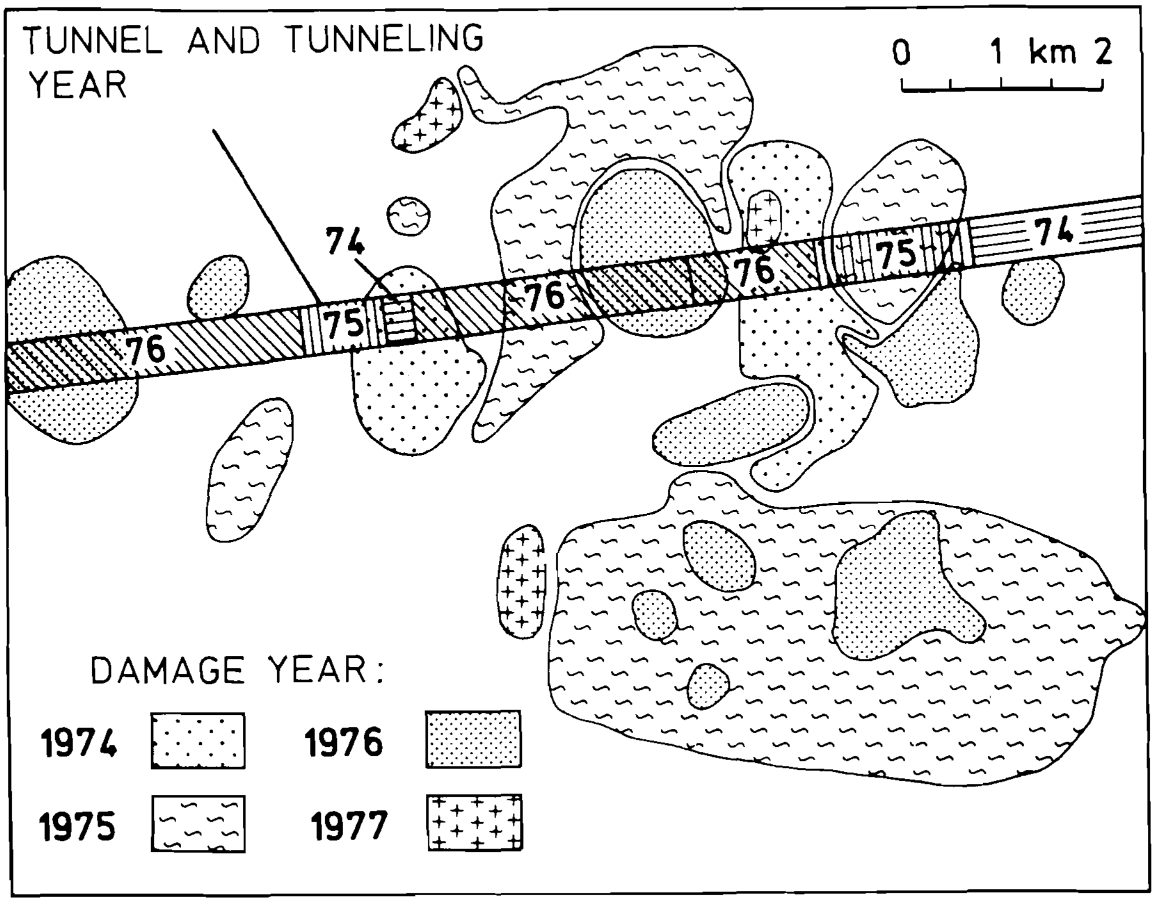

Fig. 4 - Spreading damage to plants following the Haruma tunnelling in Japan (adapted from Fukuoka, 1977).

3. RATIONAL USE OF UNDERGROUND DRAINED WATER RESOURCES

A historical and archaelogical example is provided by the Agrigento underground chambers, which successfully combined the need to drain the aquifer in order to supply the city with water and the need to convey drained water. It can be assumed that the underground chamber wells were designed to increase the passageway draining capacity. They could collect even the tiniest water dripping and speed up seepage into the passageways. Furthermore, wells were probably used to ventilate conduits and enable water uptake. Thus, they favoured flow control and gallery tunneling. Nowadays, it is known that the Agrigento's underground chambers were organically interconnected. Therefore, they fully drained the calcarenite water-bearing strata.

Water inflows are currently encountered when excavating modern tunnels, sometimes at a high rate. They suddenly occur and are difficult to predict. They account for one of the most feared of and unexpected events which can claim the lives of human beings and cause severe damage.

Nevertheless, tunnel water inflows being generally pure and drained groundwater lost in most cases, a partial recovery might be envisaged, which would reduce drawbacks on the groundwater resources involved in the tunnel works.

The total discharge rate of pure water drained from the Italian side of the Mont Blanc tunnel added up to 0.6 m^3/s (Cotecchia, 1993), that is the daily water-supply of more than 100,000 people. As for the St. Lucia tunnel, water resources collected during construction works (0.45-0.50 m^3/s discharge rate) were conveyed and lifted to supply the town of Salerno and the Amalfi coast with drinking water, by means of an underground aqueduct system (Celico et al., 1977). The work was designed and built after heavily interfering with the pre-existing hydrogeological configuration. Similar applications are recommended in order to minimize groundwater drainage drawbacks.

Therefore, the use of tunnel-drained waters may prove a profitable and sometimes necessary measure to cope with water-supply shortages in some Italian regions. To this end, water inflows encountered during tunnelling are to be thouroughly studied and investigated.

For both existing and future excavation works, drained water discharges may play a crucial economic and social role. They could be effectively used at much lower collection and conveyance costs, mostly if aqueducts and tunnels are simultaneously designed and built.

4. CONCLUSIONS

Underground space construction requirements create conditions which are generally detrimental to groundwater resources. These effects, though sometimes negligible due to the poor hydrogeological interest of the excavated medium or to the design characteristics of the excavation work, are likely to result in: a reduction in the aquifer regulation and storage capacity volume, transmissivity, water residence time, groundwater potential energy and piezometric head; a worsening of water quality; an increase in the mean water velocity and a variation in spring outflows and drained discharge rates.

Experience shows that, whenever drawbacks are predictable, an accurate hydrogeological study is recommended prior to starting construction works, in order to estimate the water resources covered by the layout. Groundwater flow numerical models may enable to determine all possible drawbacks occurring during the flow transient stage and therefore help take design measures to reduce them and guarantee a time-saving and cost-effective structure. In some cases, this study has yielded favourable results, making groundwater resources available under the best hydraulic conditions.

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