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# THE ROMAN HYDRAULIC SYSTEM OF FRIGENTO (CAMPANIA, SOUTHERN ITALY)

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## EXTENDED ABSTRACT

La necessità di fornire l'acqua all'insediamento di *Frequentum* (attuale Frigento in Campania) e alla strada che collegava *Beneventum* (attuale Benevento) a *Compsa* (attuale Conza della Campania), situata circa 35 km a SE di Frigento nella valle del Fiume Ofanto, era dettata in larga misura dalla necessità di rifornire le legioni dell'esercito romano che, per motivi strategici e politici, dovevano transitare spesso su tale strada. Essa coincideva probabilmente con il tracciato della Via Appia antica tra *Aeclanum* e *Venusia* (attuali Mirabella Eclano e Venosa). Le cisterne del sistema idraulico, di età tardo-repubblicana (circa 86-27 a. C.), suggeriscono che *Frequentum* era un importante centro romano.

L'area di Frigento è ubicata su un rilievo a quota 910 m s.l.m., compreso in una dorsale orientata NW-SE che forma lo spartiacque tra il bacino idrografico del Fiume Ufita a NE e quello del Fiume Calore a SW, ed è costituita dal Flysch galestrino del Cretacico, caratterizzato da un grado di permeabilità relativa molto basso. Una coltre di suolo di colore grigio scuro con spessore fino a 5 m è presente nella zona sommitale dell'area urbana e in parte su versanti. L'analisi granulometrica di un campione di suolo ed una prova di permeabilità in situ indicano che si tratta di un suolo sabbioso limoso il cui coefficiente di permeabilità è E-05 m/sec.

I dati climatici, rilevati presso la vicina stazione di S. Angelo dei Lombardi alla stessa quota di Frigento e disponibili solo per il 2005, 2006 e 2008, forniscono i seguenti valori medi: temperatura 11,6°C, precipitazioni totali 796 mm, evapotraspirazione 517 mm, precipitazioni efficaci 279 mm. L'infiltrazione totale efficace interna è compresa tra $0{,}223 \times 10^{-3}$ e $0{,}251 \times 10^{-3}$ $m^3$/anno.

La parte attualmente osservabile del sistema idraulico è costituita da 4 gallerie, di cui tre visitabili, perchè la quarta è interrata. Le gallerie sono parallele ed adiacenti con asse orientato NW-SE, hanno forma rettangolare e sono lunghe 21 m, larghe circa 2 m. L'altezza misurata perpendicolarmente all'asse della calotta è 3,90 m, i piedritti sono alti 2,57 m con spessore di 0,60-0,70 m e il pavimento è protetto da una griglia metallica. Per la costruzione delle gallerie è stato necessario procedere prima alla escavazione del suolo e del Flysch galestrino su una zona rettangolare. Successivamente sono stati costruiti i piedritti e le calotte e infine è stato depositato il livello di suolo permeabile sopra le calotte. Queste ultime sono state sottoposte ad un trattamento tale da consentire che l'acqua accumulata nel suolo sovrastante potesse filtrare attraverso di esse. Il materiale calcareo di risulta è stato utilizzato per le strutture murarie, le calotte e il rivestimento. Infatti tutta l'opera idraulica è edificata con *opus caementitium* rivestito con paramento esterno in *opus incertum*. I due tipi di *opus* comprendono conci di calcari marnosi di colore grigio e calcari silicei di colore marrone o giallastro di varie dimensioni. Sono presenti anche alcuni conci di travertino, prelevato dalle cave circa 6 km a sud di Frigento, che è il materiale utilizzato nei piedritti e nell'arco delle aperture che collegano le tre gallerie. La malta idraulica è costituita da inerti calcarei con granulometria della sabbia grossolana immersi in una matrice di colore grigio e grigio scuro composta dal suolo che affiora nella zona e da calce.

Le gallerie intercomunicanti rappresentano un articolato sistema idraulico costruito con materiali impermeabili per immagazzinare, durante l'intero anno, l'acqua delle precipitazioni e quella derivante dalla fusione della neve raccolte su una superficie pressoché pianeggiante di circa 26.000 $m^2$ a 900 m s.l.m., dove esiste un livello di suolo permeabile sufficientemente spesso sovrapposto al Flysch galestrino praticamente impermeabile. Si evitava in tal modo la raccolta di acqua in cisterne a cielo aperto, ottenendo una potabilità di gran lunga migliore. L'ordine di grandezza del volume di acqua che il suolo avrebbe potuto assorbire in un anno sulla superficie di circa 26.000 $m^2$ è compreso tra 5.798 e 6.256 $m^3$. Questi valori sono considerati minimi perché si dovrebbe aggiungere la quantità di acqua derivante dalla fusione della neve, non valutabile per la mancanza di dati sulle precipitazioni nevose.

## ABSTRACT

The Romans solved the problem of supplying water to the settlement corresponding to modern Frigento (910 m a.s.l.) and to the road connecting modern Mirabella Eclano to modern Conza della Campania by constructing a storage system consisting of a series of cisterns. The latter were excavated in Cretaceous Flysch galestrino with the least degree of relative permeability, lying -below a surface level of pyroclastic sandy soil up to 5 m thick with a medium degree of relative permeability. The volume of water that the soil could have absorbed in one year over the 26,000 $m^2$ - surface enclosed in the contour line 900 m a.s.l. ranges between 5,616 and 6,256 $m^3$. This should be considered as a conservative estimate, since it does not include the quantity derived from melted snow, which cannot currently be computed due to lack of specific statistical data. The water thus accumulated in the cisterns formed a reserve available throughout the year.



***Key words***: *cistern, hydraulic system, Frigento, permeable soil, hydric reserve*


## INTRODUCTION

The Romans made considerable technical advances in hydraulics, expanding the knowledge they inherited from the Hellenistic civilization. The Greeks had already given a great impetus to the science through the contributions of eminent scholars such as Thales, Euclid, Pythagoras and Ctesibius. The latter, in particular, performed fundamental research on the design and construction of hydraulic devices (pumps and hydraulic organs) and instruments of measurement (water-clock). Water played a central role in Roman civilization and culture, for drinking, cleaning, bathing, socialising and relaxation. An abundant supply was needed for bath complexes, ornamental nymphaea and monumental fountains. The provision of a water supply, together with Roman law and the might of the army, thus became both an instrument of political power and a justification for dominion over other populations.

During the first few centuries after the city's foundation, the Romans used the waters of the River Tiber. Later, this was supplemented by water derived from springs and wells, together with rain water stored in cisterns built in the urban territory of Rome. By the end of the 4th century BC this was no longer sufficient and the first of a series of aqueducts was built to canalize water derived from springs located up to 80 kilometres from the city.

Our main sources today of information about the Romans' technical ability to construct hydraulic works are two treatises by Roman authors. The first, *De Architectura*, is a treatise by Marcus Vitruvius Pollio (c. 80-15 BC), dedicated to emperor Augustus, illustrating research systems, methods used to evaluate water quality, aqueduct construction criteria and water storage methods. The second, *De Aquaeductu Urbis Romae*, is a treatise by Sextus Julius Frontinus (40-103/104 BC) which describes in detail nine of the eleven aqueducts that fed the city of Rome (the Aqua Traiana and Aqua Alexandrina aqueducts were constructed after Frontinus died).

Rain water storage systems are a very ancient technology, in widespread use all over the world. The Romans adopted this type of system in particular where water resources were very limited or lacking, as in the entire territory of the town known today as Frigento, located in the Campania region and characterized by unfavourable hydrogeological conditions. Thus in this challenging context the Romans faced the problem of supplying water to the *Frequentum* settlement (modern Frigento) and to the road that connected *Beneventum* (modern Benevento), to *Compsa* (modern Conza della Campania), about 35 km SE of Frigento in the valley of the River Ofanto (Fig. 1). This road was very important because it passed close to the temple of the Goddess Mefitis, whose worship was connected with emissions from the ground of carbon dioxide and hydrogen sulphide. *Compsa* itself became a very relevant strategic centre during the period of the three Punic wars of Rome against Carthage (fought respectively in 264-241 BC, 218-202 BC and 149-146 BC); indeed, Hannibal camped there in 216 BC after winning the battle of Cannae. The origins of *Frequentum* date back to the fifth century BC when the Samnitic League, of which the Irpini were part, tried to resist Rome during three wars (fought respectively in 343-341 BC, 326-304 BC and 298-290 BC). At the end of the Samnite wars *Frequentum* was conquered with other cities and became a Roman centre.

The Romans' main purpose in creating a supply of water was to provide for the Roman army who frequently used the road from *Beneventum* to *Compsa* for strategic and political reasons. Indeed, it is believed that the hydraulic system of *Frequentum* was constructed in function of supplying the road and that it coincided with the route of the old Appian Way (Fig. 1) between *Aeclanum* and *Venusia* (modern Mirabella Eclano and Venosa). The old Appian Way, begun in 312 BC by censor Appius Claudius Caecus, was a thoroughfare of vital importance because it crossed the regions of Campania, Lucania and Apulia, connecting Rome to the port of *Brundisium* (modern Brindisi) and thus to the Orient.

The present study is part of the project entitled "Investigation into the route of the old Appian Way between Mirabella Eclano and Venosa" of the National Association for the Interests of Southern Italy (A.N.I.M.I.) and the Institute for the Archaeological and Monumental Heritage (I.B.A.M.) of the National Research Council (C.N.R.). It aims to illustrate the criteria governing the construction and functioning of the hydraulic system that supplied water to an important Roman settlement and to the road connecting *Beneventum* to *Compsa*.

## GEOGRAPHIC AREA AND GEOLOGICAL SETTING

Modern Frigento is a small hill town (910 m a.s.l) lying on a ridge lying NW - SE that forms the watershed between the hydrographic basin of the River Ufita to the north-east and that of River Calore to the south-west (Fig. 1). This area is located in the southern Apennine chain, between the Tyrrhenian Sea to the south-west and the Adriatic-Apulian foreland to the north-east (Fig. 2). This chain underwent its last compressive buckling between the late Pliocene (3.60 Myr) and early Pleistocene (1.81 Myr) (Mostardini & Merlini, 1986; Patacca *et alii*, 1989; 1990; 1993; Scrocca *et alii*, 2003). Extensional tectonics, on the other hand, affected the Tyrrhenian area and the western part of the chain from the late Tortonian (about 7.30 Myr) and resulted in the development of piggy-back basins during the Pliocene, and of basins between the mountains and the alluvial plain areas in the Pleistocene. Furthermore, the Campania region is characterized by the volcanic centres (Fig. 2) of Somma-Vesuvio (0.4 Myr - 0), Campi Flegrei (0.06 Myr - 0) and the Island of Ischia (about 0.15 Myr - 0) that were active during the middle to late Pleistocene (Scrocca *et alii*, 2003).

The southern Apennine chain is the result of buckling of five sectors of a palaeogeographic model including, from west to east, the following belts (Mostardini & Merlini, 1986): the Ligurids and the Tyrrhenian basin, the Apennine carbonate platform, the Lagonegro - Molise basin, the Apulia inner carbonate platform, the Apulia basin and the Apulia outer carbonate platform. Several tectonic units have been identified in the southern Apennine chain. In the study area of the Campania region they consist mainly of the Fortore Unit (Pescatore *et alii*, 2000; 2008) thrust on the Lagonegro Unit (Scandone, 1967; 1972: 1975; Fig. 3). The former includes the Cretaceous - early Miocene Varicoloured Claystone Formation and the early Miocene Numidian Flysch. The latter unit is made up of the middle Triassic Formation of Mt. Facito, the late Triassic Formation of limestones with chert, the Jurassic Siliceous schists and the Cretaceous Flysch galestrino (Fig. 3).

## MATERIALS AND METHODS

For this study on the Roman hydraulic system of Frigento, an historical investigation, a geological survey of both the Frigento zone in scale 1: 25,000 and of the urban centre in scale 1: 1,000 and a hydraulic survey of the water storage structure were performed. Climatic data were also evaluated (yearly rainfall and mean temperatures), using data from the St. Angelo dei Lombardi

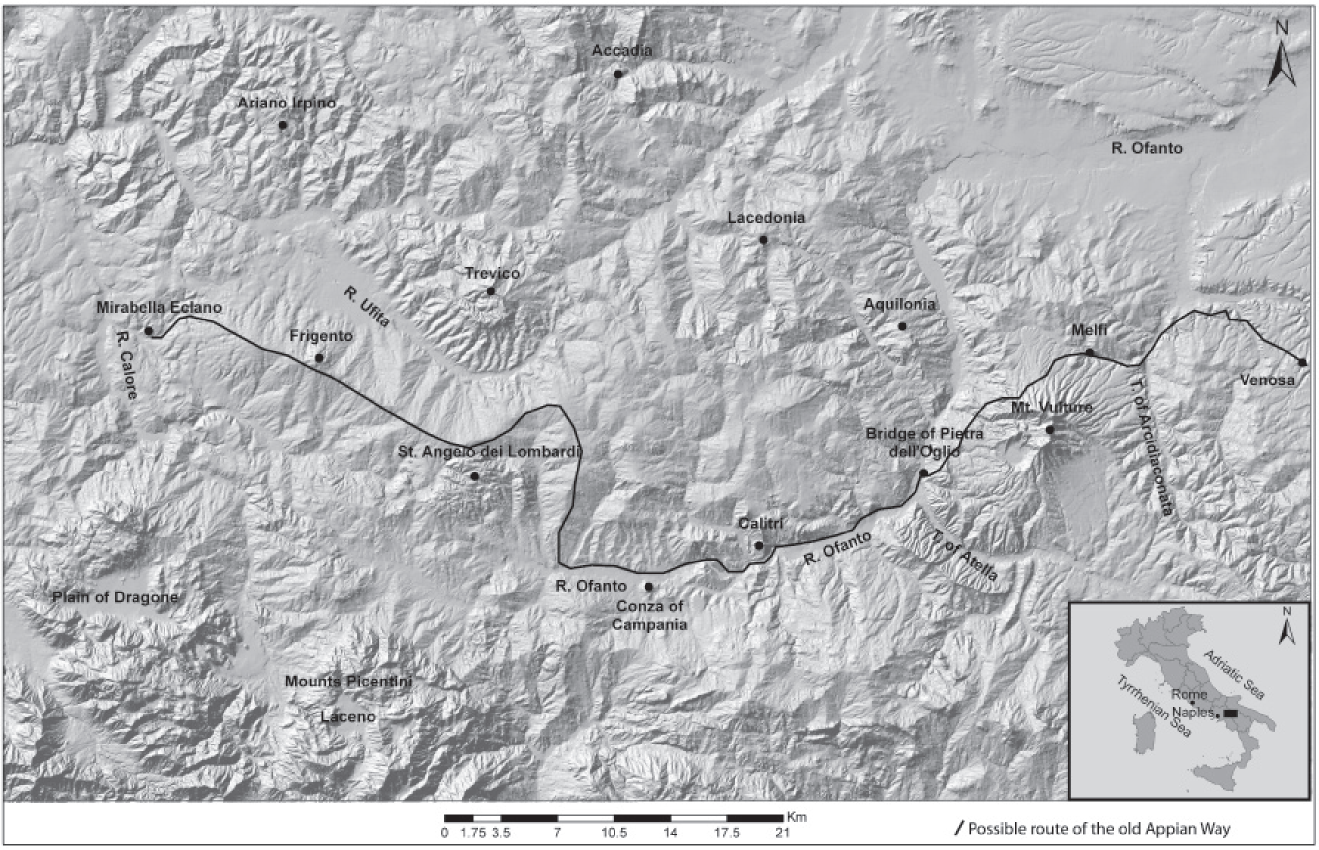


*Fig. 1 - Digital Terrain Model showing the location of Frigento and the possible route of the old Appian Way followed between Mirabella Eclano and Venosa*

station (875 m a.s.l.) about 15 km SE of Frigento, since Frigento has no station recording. These data are available for 2005, 2006 and 2008 only, whilst no snow precipitation data are available. Furthermore, a grain size analysis and a permeability test in situ were performed on soil in accordance with the Recommendations of AGI (1977) and the volume of water that the soil could store in one year was estimated.

## RESULTS

*Historical information*

The first direct historical information reported here on the hydraulic system of Frigento derives essentially from works written by local two scholars: Fabio Ciampo (1798; 1837) and Pietro Gaetano Flammia (1845). According to Ciampo (1798), the old people of the town informed him there were eleven underground chambers, only four of which were visible, interconnected through small arch-shaped openings. Ciampo reported their height as fourteen and a half spans (1 span = 26.45 cm; fourteen and half spans = 3.83 m); their width as seven and a half spans (1.98 m), while their length was undefined in that period. These chambers running towards the east and south, are sloped and narrowed from place to place so that reserves of water are retained. One of these pools is visible and ends in a narrow channel about 2 spans in diameter, that can be seen in one point where there is a channel with a 2 span diameter (about 53 cm). They are known as 'wells' and are used to provide the city with rain water.

Furthermore, the author noted that when the tunnels were cleared, "*the base of a Tuscan order pillar with a diameter of 4 spans less one inch* [Author's note: c. 103 cm] *and an inscription naming the architect as C. Antistius Isocrysus*". In a later work Ciampo (1837) added that the four tunnels were connected to "*other similar chambers*" present "*throughout City*" and that they consist of two more parts: that is to say, square cisterns where the arches of the wells end, whence more narrow channels start like nerves to form ganglions and further on start again to form other ganglions… above the chamber we see some narrow channels with a diameter of two and half spans [66 cm] lined with bricks.

Flammia (1845) claimed, instead, that there were five wells "*in part untouched, symmetrically positioned in the form of corridors, about 200 spans long [c. 53 m] and fourteen spans high [3.7 m] recognizable among crumbling ruins*".

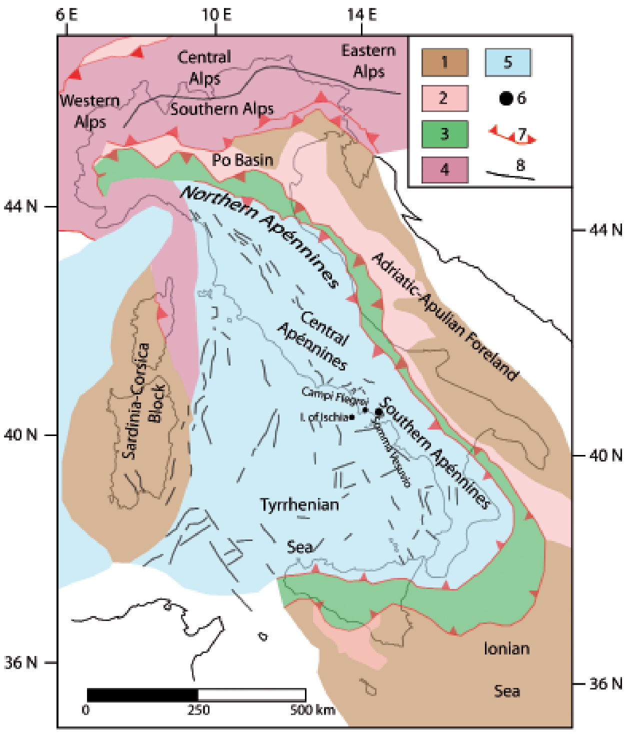


*Fig. 2 - Schematic tectonic map of Italy. From Scrocca et alii (2003) modified. 1, foreland areas; 2, fore-deep sediments; 3, Apennine areas characterised by a compressional tectonics; 4, thrust belts of the Alps and Corsica connected to the Alpine orogenesis; 5, areas with extensional tectonics of the Apennines and Tyrrhenian Sea; 6, volcanic centre; 7, main thrusts; 8, faults*

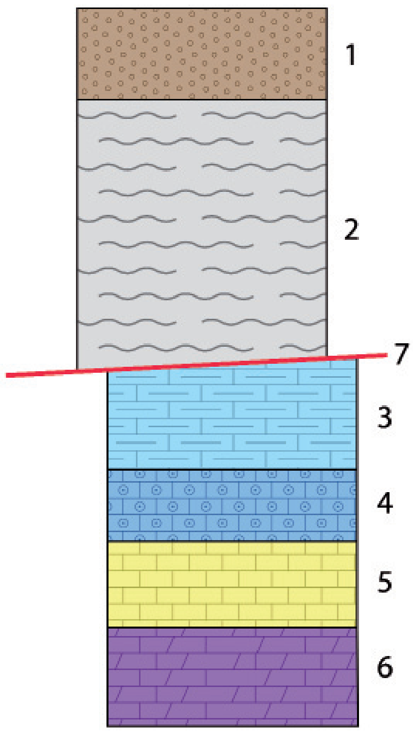


*Fig. 3 - Stratigraphic-structural scheme of the relationships between the Fortore Unit and the Lagonegro Unit.*
*Fortore Unit: 1, Numidian Flysch (early Miocene); 2, Varicoloured Claystone Formation (Cretaceous - early Miocene); 7, thrust. Lagonegro Unit: 3, Flysch galestrino (Cretaceous) 4, Siliceous schists (Jurassic); 5, Formation of limestones with chert (late Triassic); 6, Mt. Facito Formation (middle Triassic)*

Then archaeological excavations carried out in 1958 by the Antiquity Service of Campania (Onorato, 1960) to investigate the hydraulic system also known as the "*Roman cisterns*", brought to light an inscription of the era of Lucius Cornelius Sulla Felix found in a pillar of the church of S. Maria Assunta (Degrassi, 1972; Colucci Pescatori, 1975). This inscription records the fact that "*a wall, some doors, a forum, a portico, a curia and a cistern were constructed by Caius Quinctius Valgus*" (Colucci Pescatori, 1975). Quinctius Valgus was a duumvir, i.e., a magistrate employed on delicate political and administrative tasks with a one year term of office, and a supporter of Sulla; he also served as plebeian tribune in 63 BC (Ebanista, 2009). Later, on occasion of works in Frigento connected with the 1980 Campania-Lucania earthquake, the remains of the suspensurae of a Roman bath house dating between 1st and 2nd century AD were found in Via S. Pietro, while in Via S. Giovanni a water duct with a double sloping cover consisting of bipedal bricks was discovered (Colucci Pescatori, 1991; Romito, 1995; Giovanniello & Forgione, 1999; Colucci Pescatori, 2000). A further segment of water duct was unearthed in 1998 in Via S. Giovanni during road works in connection with the gas supply (Mauriello, 2005).

The late republican age cisterns dating about 56-27 BC (Onorato, 1960; Romito, 1975; Giovanniello & Forgione, 1999; Colucci Pescatori, 2000; Forgione & Giovanniello, 2002), the water duct consisting of bipedal bricks in Via S. Giovanni and the 1st to 3rd century BC wall structures found below the church of S. Pietro suggest that *Frequentum* was an important Roman centre, referred to as a *vicus* and/or an *oppidum*, or as a colony and/or a duoviral *municipium* (Colucci Pescatori, 2000).

*The geological setting of Frigento*

The geological survey (Fig. 4) of the Frigento area confirmed that the calcareous-marly member of the Varicoloured Claystone Formation overlies the Flysch galestrino. The former includes medium and thick beds of turbidite calcarenites and calcirudites with intercalations of thin beds of red and green marls. The latter consists of medium, thick and very thick beds of grey and yellowish marly limestones with calcite veins, siliceous limestones with a brown colour due to films of iron oxides, and grey and brown marls and claystones. The Flysch galestrino is buckled in a succession of asymmetrical closed folds, whose axis is oriented in a NW-SE direction (Fig. 4) and

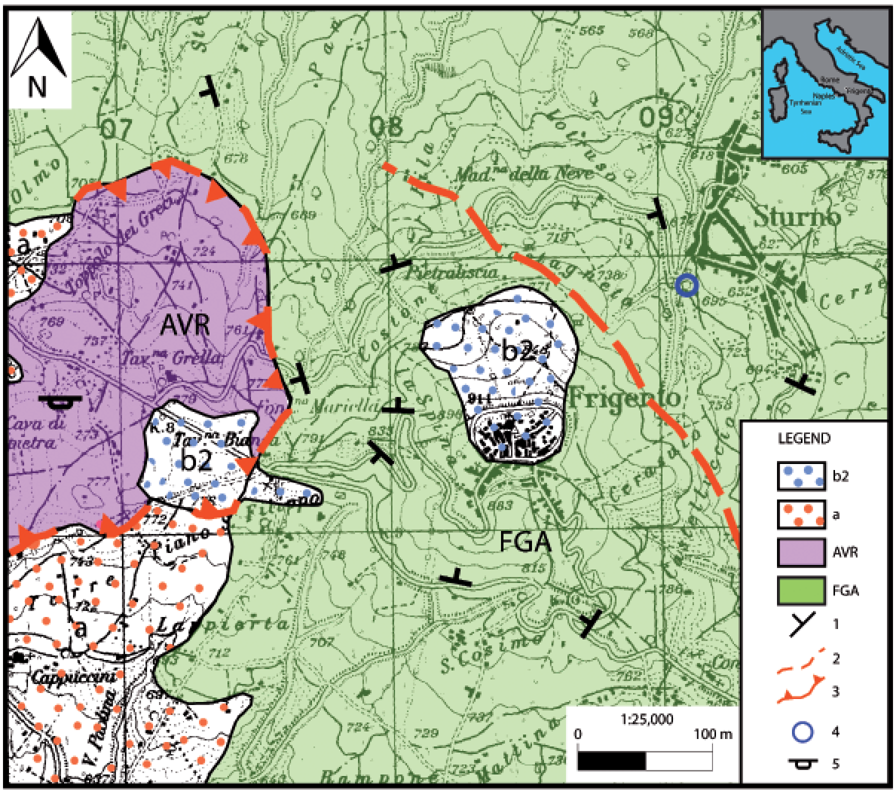


*Fig. 4 - Geological map of the Frigento area.*
*b2, soil (Holocene); a, debris (Holocene); Fortore Unit: AVR, calcareous - marly member of the Varicoloured Claystone Formation (Cretaceous - early Miocene); Lagonegro Unit: FGA, Flysch galestrino (Cretaceous); 1, bed attitude; 2, probable normal fault; 3, thrust; 4, spring; 5, abandoned quarry*

it is characterized by the least degree of relative permeability. A typical dark grey soil with a thickness of up to 5 m (Fig. 4) rests partly on the Flysch galestrino in the upper zone of the urban area and partly on the slopes. A grain size analysis of soil sampled in the excavation for the *in situ* permeability test (Fig. 5) shows that the soil consists of silty sand (Fig. 6). This deposit was produced by weathering of the pyroclastic deposits resulting from the Somma-Vesuvio volcanic eruptions.

*Climatic elements*

As regards climatic conditions, it should be borne in mind that past environmental conditions, in particular precipitation levels, were similar to the current conditions for long periods, favouring anthropogenic activities and socio-economic development, as occurred between 350 and 150 BC, taking into account also the Small Ice Age between 520 BC and 357 AD (Ortolani & Pagliuca, 2007). Climatic data (yearly rainfall and mean temperatures) are available for 2005, 2006 and 2008 only.

The mean recorded temperature (*Tm*) is 11.6°C and the monthly means range between a minimum of 2.9°C in February and 5.5 °C in January and a maximum of 21.6°C in July and 20.8 °C in August (Tab. 1). The total rainfall (*Ptot*) shows a mean annual value of 796 mm (Tab. 1) which is concentrated in the period from November to April, during which period values of 620 mm (c. 85% of the annual total), 413 mm (c. 61%) and 732 mm (c. 75%) were recorded in 2005, 2006 and 2008 respectively. The real evapotranspiration (*Er*) was calculated by means of Turc's formula (1954):

$$Er = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}}$$

where *P* is the yearly precipitation and *L* is a parameter function of the yearly mean temperature T in °C:

$$L = 300 + 25T + 0.05T^3$$

The mean value of *Er* (Tab. 1) is 517 mm, with a maximum value of 485 mm in 2006 and a minimum value of 564 mm in 2008.

The effective rainfall (*PE*) represents the renewable potential natural total water resources and was calculated yearly by sub-


*Fig. 5 - Map of the upper part of Frigento showing the distribution of soil and the location of cisterns, permeability test and sampling of soil*

tracting the evapotranspiration from the total rainfall:

$$PE = Ptot - Er$$

The mean value of effective rainfall *PE* (Tab. 2) is 279 mm with a maximum value of 413 mm calculated for 2008 and a minimum value of 200 mm for 2006.

The internal effective total infiltration (*Iti*) was calculated on the basis of the rainfall, temperature, real evapotranspiration and effective rainfall data, obtained using the potential infiltration coefficients (*p.i.c.*) proposed by Celico (1986; 1988; Tab. 3), which allow to evaluate the yearly infiltration as a part of the effective rainfall. The Iti value varies according to the lithology of the feeding area depending on its degree of relative permeability. Since the urban area of Frigento is covered by sandy soil, the 80-90 percent coefficient typical of sands is suitable. Based on this coefficient, the Iti value ranges between 0.223 $x10^{-3}$ and $0.251x10^{-3}$ $m^3$/year.

*The permeability test in situ*

This test was carried out under constant head conditions in the north-eastern zone of Frigento (Fig. 5) close to the crossroad between Via Limiti and Via S. Giovanni (42° 00.797' N; 15° 06.074' E) in order to define the hydraulic conductivity of the soil. A steel ring with a height and diameter of 25 cm was inserted into a 60 x 60 x 60 cm hole excavated for the purpose and the soil was completely saturated before starting the test. Figure 7 shows a graph of the hydraulic conductivity coefficient value, K. It can be seen that the initial value of K was of the order of E-06 m/s, which increased rapidly to a value of E-05 m/s, which is in good agreement with the grain size composition of soil defined as silty sand.

## *The hydraulic water storage system*

The hydraulic system was constructed in the area of maximum elevation of the route of the road connecting *Beneventum* to *Compsa*, after exceeding a gradient of about 400 m between *Aeclanum*, at 400 m a.s.l., and the area of *Frequentum* at 800 m a.s.l.

The part of the hydraulic system which is visible today consists of four tunnels, of which only three can be visited, be-

| Year | Ptot | Tm | L | Er |
|---|---|---|---|---|
| 2005 | 727 | 11.4 | 659 | 501 |
| 2006 | 685 | 11.3 | 654 | 485 |
| 2008 | 977 | 12.2 | 696 | 564 |
| N | 3 | 3 | 3 | 3 |
| MA (mm, °C) | 796 | 11.6 | 670 | 517 |
| MAX (mm, °C) | 977 | 12.2 | 696 | 564 |
| MIN (mm, °C) | 685 | 11.3 | 654 | 485 |

*Tab. 1 - Calculation of the real evapotranspiration by means of Turc's formula (1954) for 2005, 2006 and 2008*

| *Year* | *Ptot* | *Er* | *PE* |
|---|---|---|---|
| 2005 | 726 | 501 | 225 |
| 2006 | 685 | 485 | 200 |
| 2008 | 977 | 564 | 413 |
| N | 3 | 3 | 3 |
| MA | 796 | 517 | 279 |
| MAX | 977 | 564 | 413 |
| MIN | 685 | 485 | 200 |

*Tab. 2 - Calculation of the variations of effective rainfall in 2005, 2006 and 2008. Ptot, total rainfall; Tm, mean temperature; L, 300 + 25T + $0.05T^3$; Er, real evapotranspiration in mm/year; PE, effective rains; N, number of observations; MA, arithmetic mean; MAX, MIN, respectively maximum value and minimum value*

| Hydrogeological complexes | p.i.c. % | Hydrogeological complexes | p.i.c. % |
|---|---|---|---|
| limestones | 90 - 100 | lavas | 90 - 100 |
| dolomite limestones | 70 - 90 | pyroclastic deposits | 50 - 70 |
| dolostones | 50 - 70 | pyroclastic rocks and lavas | 70 - 90 |
| marly limestones | 30 - 50 | intrusive rocks | 15 - 35 |
| coarse debris | 80 - 90 | metamorphic rocks | 5- 20 |
| alluvial deposits | 80 - 100 | sands | 80 - 90 |
| clayey-marly-arenaceous deposits | 5 - 25 | clayey sands | 30 - 50 |

*Tab. 3 - Values of the potential infiltration coefficients (p.i.c.) of some hydrogeological complexes according to Celico (1986; 1988)*

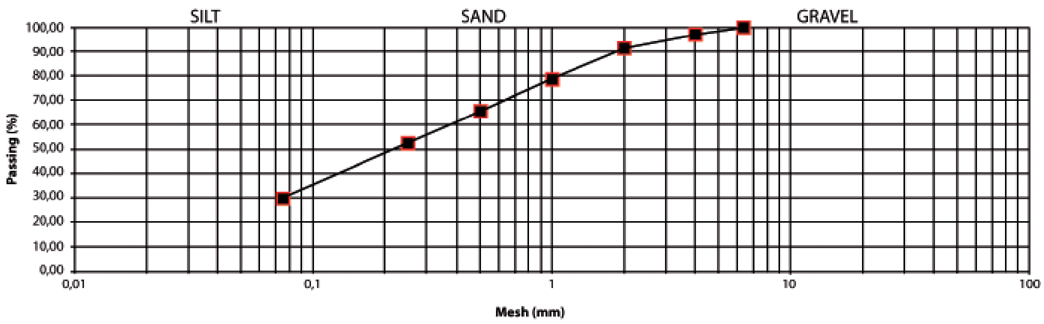


*Fig. 6 - Cumulative curve showing the grain size composition of the soil sampled in the excavation for the permeability test in situ*

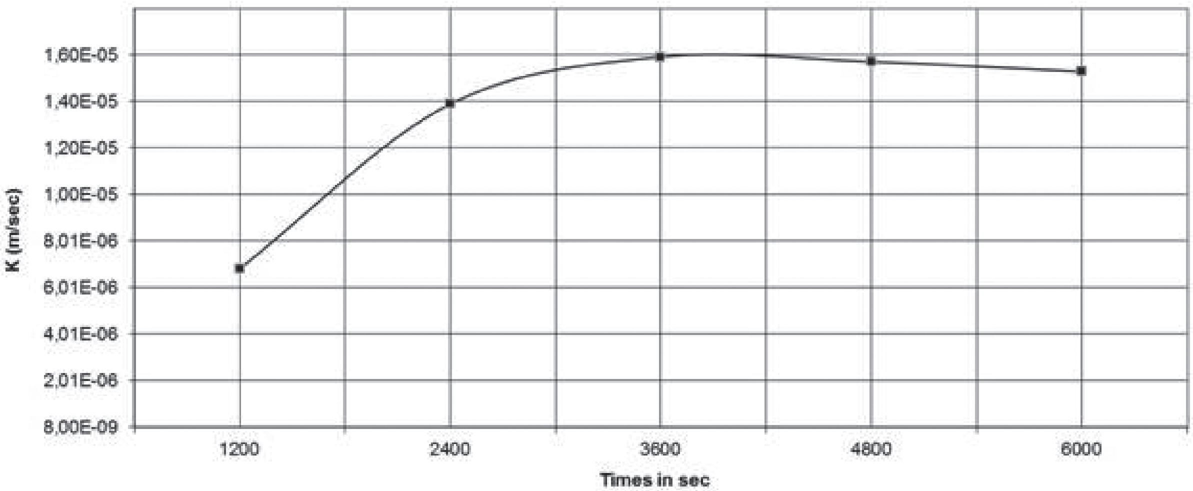


*Fig. 7 - Graphs showing the trend of values of the hydraulic conductivity coefficient K during the permeability test in situ under constant head conditions*

cause the fourth has been filled in (Fig. 8). According to Ciampo (1798) there should be eleven tunnels in the village, although the location to which the tunnels lead is unknown. The entrance of the four known tunnels, are currently located in a small square at 908 m a.s.l. (Fig. 5) below a building and its garden (41° 00.776' N; 15° 0.41' E). They can be reached by means of a staircase consisting of fifteen steps, so that the floor of the three tunnels lies about 3 m below ground level at 904.7 m a.s.l. (Figs. 8 and 9).

The three tunnels that can be visited are in surprisingly good condition. They lie parallel and adjacent to a NW-SE axis and are rectangular in shape, 21 m long and about 2 m wide. The height measured perpendicularly to the axis of the crown is 3.90 m (Fig. 8), the piers are 2.57 m high and 0.60-0.70 m wide and the floor is protected by a metallic grid. The measurements of the tunnels' dimensions are slight different from those reported by Ciampo (1738). The floor is inclined on a 1% slope allowing water to flow towards the entrance. The three tunnels are connected through two perfectly aligned arch-shaped openings 0.60 m wide and 1.15-1.50 m high. The arch-shaped opening of tunnel n. 1 is 8.40 m away from its entrance (Fig. 10).

There is a fourth opening for access to tunnels 2 and 3 which has three buttresses 0.90 m wide and the same height as the piers, constructed to balance the pressure of the soil, and a wall that reduces the length of the tunnel. There are some holes in the piers close to the floor, these probably served either to facilitate ventilation in the lower part of tunnels, where the circulation of air is poor, or to solve problems of statics due to variations of pressure during the phases of emptying and filling of the cisterns. Furthermore in the middle part of the crown there is a circular cavity with a diameter of 0.70 m for drawing up water which is currently filled in. A second circular cavity rises perpendicularly upward as far as ground level of the garden overlying the three tunnels. This opening, which is protected by a metallic grid, was clearly intended to be used as a well to draw water from the tunnels. The crowns have been subjected to repairs in concrete carried out in modern times which have changed their original structure, through which the water derived from the overlying soil should filter down into the tunnels. The soil and Flysch galestrino over a rectangular zone would have had to be excavated in order to construct the tunnels. Later the crown and the piers would have been constructed and lastly a level of permeable soil would have been deposited above the crown. The crowns would have undergone a procedure to allow the water which had accumulated in the overlying soil to filter through them. The resulting calcareous material would have been used for the wall structures and the covering. In fact the whole hydraulic system was constructed using *opus caementitium* (Roman concrete) covered by an outer surface consisting of *opus incertum* (irregular masterwork). This types of *opus* includes ashlars of gray marly limestones and brown or yellowish siliceous limestones (Fig. 11) of various dimensions. Travertine, derived from quarries about 6 km south of Frigento, was used for the piers and arches of the openings connecting the three tunnels and a few ashlars of travertine are also present in the covering (Fig. 10). The hydraulic mortar consists of calcareous sandy grain-sized inerts and a grey to dark grey matrix including the pyroclastic soil outcropping in the zone and the lime (Fig. 11).

The interconnected tunnels are an articulated hydraulic system constructed with impermeable materials to store the rain water and the water derived from melted snow, which are particularly abundant during the November to April period. Thus the collecting of water in open cisterns was avoided, resulting in a much better quality of drinking water.

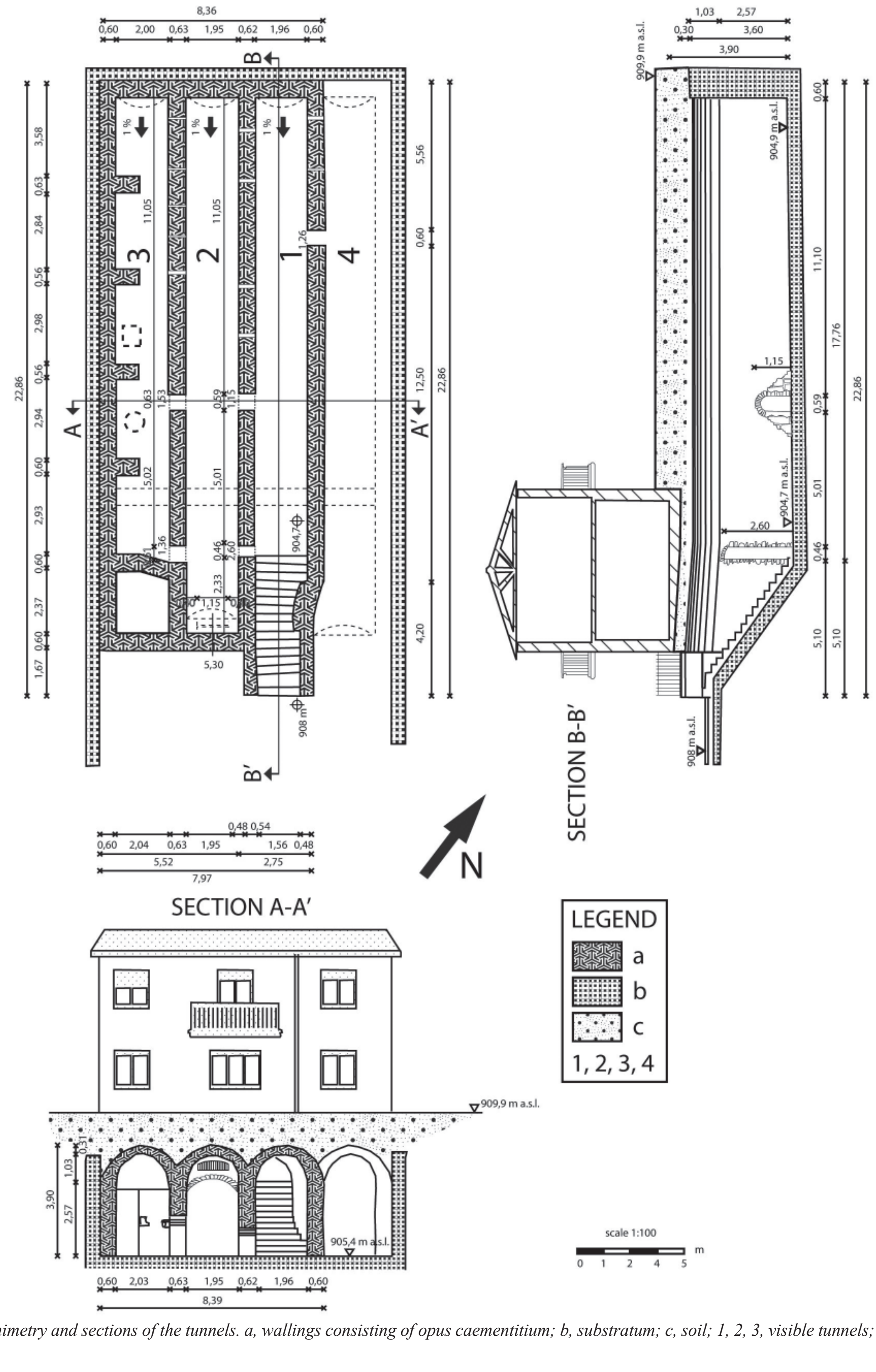


*Fig. 8 - Planimetry and sections of the tunnels. a, wallings consisting of opus caementitium; b, substratum; c, soil; 1, 2, 3, visible tunnels; 4, tunnel filled in*

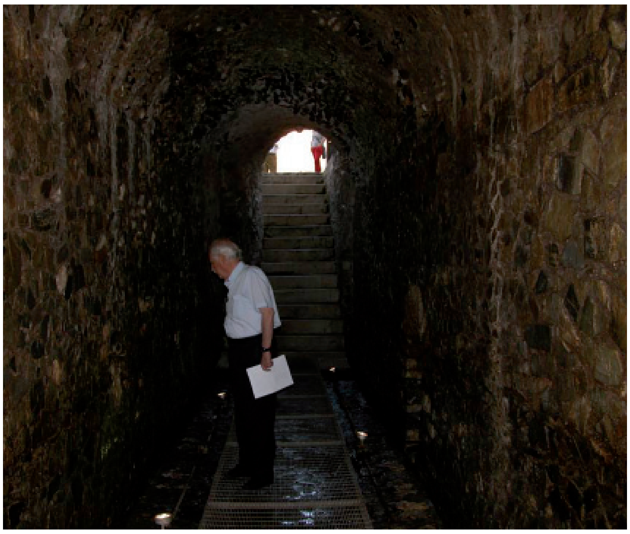

Fig. 9 - *Tunnel n. 1 with the floor protected by a metallic grid and the staircase of access*

Fig. 10 - *The opening in tunnel n. 1 consists of ashlars of travertine*

Fig. 11 - *Ashlars of marly limestone and siliceous limestone cemented by gray hydraulic mortar with white calcareous inerts of the face of tunnel n. 1*

*Estimation of the volume of water stored in the soil*

The Romans solved the problem of supplying water to the *Frequentum* settlement and the road running below the town connecting *Aeclanum* to *Compsa* by constructing an hydraulic system which allowed rainfall and melted snow to be stored at the highest elevation of the *Frequentum* relief, 900 m a.s.l., where a sufficiently thick layer of permeable soil caps the lithotypes of the Flysch galestrino having the least degree of permeability. When the Romans built the Frequentum settlement, the surface area of about 26,000 m$^2$ enclosed in the contour line 900 m a.s.l. was not as intensely built up as it is today and consequently the surface area must have been available for collecting and filtering precipitation. The solution which takes into account only the surface enclosed in the contour line 900 m a.s.l. was chosen in order to exclude the adjoining surfaces, which slope downwards rapidly in all directions, and would therefore favour the washing away of rain water and snowmelt along the slopes. The surface area considered was arranged with gentle slopes to favour the flow of all precipitation towards the rectangular area where the cisterns are situated (Fig. 12). Thus the Romans could rely on a quantity of rainfall that, minus the evapotraspiration, would almost completely infiltrate the permeable soil. Taking into account that the value of internal total infiltration in the soil ranges between 0.223x10$^{-3}$ and 0.251x10$^{-3}$ m$^3$/year, it is possible to estimate that the volume of the water that could have infiltrated through the soil over a surface of about 26,000 m$^2$ during one year ranged between 5,798 and 6,526 m$^3$. These quantities should be considered as minimum values to which the water derived from melted snow should be added, but this quantity cannot be estimated due to the lack of information about this type of precipitation. Thus the water filtered through as much as 5 m of soil and would come straight into contact with the crown of the tunnels and accumulate at the bottom of the tunnels, forming a reserve available during the whole year (Fig. 13).

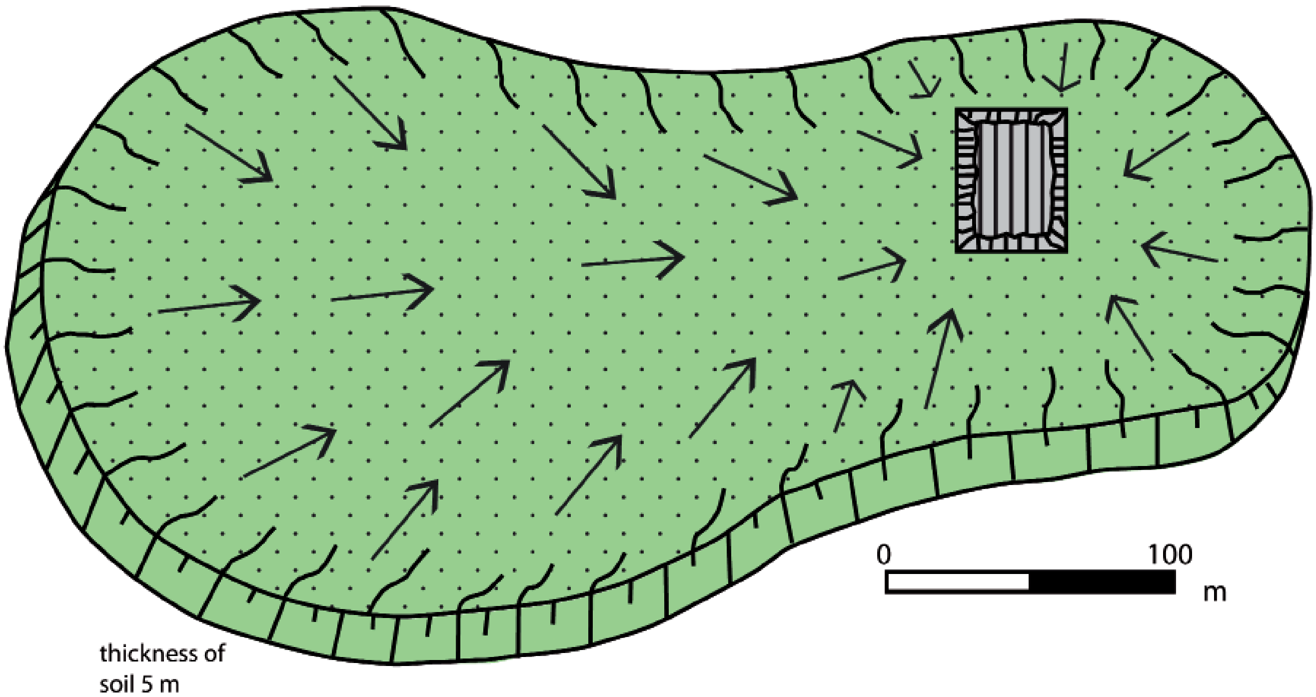


*Fig. 12 - Arrangement of the surface enclosed in contour line 900 m a.s.l favouring flow of precipitation towards the rectangular zone of cisterns*

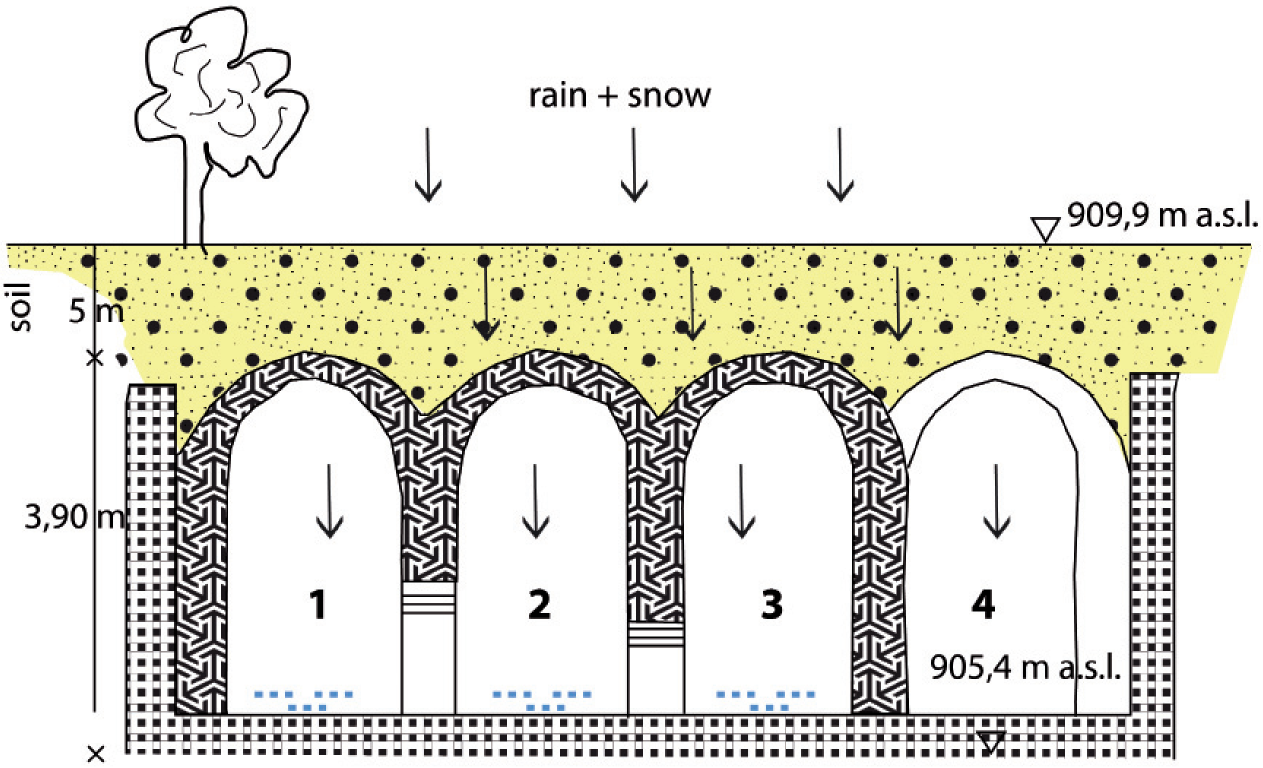


*Fig. 13 - Scheme showing the storage of rain water and snowmelt*

## CONCLUSIONS

The water derived from precipitation and melted snow and stored in the cisterns was a reserve guaranteed by the favourable climatic conditions of the *Frequentum* area, which was available the whole year round and depurated as a result of the filtering which took place as it passed through a sufficient thickness of soil. The water resource was distributed to the whole settlement by pipelines and carried down as far the road connecting *Aeclanum* to *Compsa* at 800 m a.s.l., utilizing a system of minor basins, some of which are still to be found in the town centre of Frigento today, which also served to reduce the water pressure resulting from the sudden change in altitude. The present study points out once more the notable talent of the Romans as planners operating in very varied, and often very difficult environmental and climatic conditions. It shows not only that they were very well aware of the technical properties of geological formations, utilized either as materials for civil engineering, or for constructing hydraulic systems, but also to what extent they were able to exploit these hydrogeological characteristics.

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