Hydraulic Structures in Ancient Rome. Mid-Week Technical Field Trips, MT1 Field Guide, Wednesday September 16th.

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Mid-Week Technical Field Trips
WEDNESDAY SEPTEMBER 16th, 2015

MT1 HYDRAULIC STRUCTURES IN ANCIENT ROME

Leaders:
Walter Dragoni and Costanza Cambi

FIELD TRIP GUIDEBOOK

The conduit of New Anio measures 58,700 paces, of which 49,300 are in an underground channel, 9,400 paces above ground on masonry; of these, at various points in the upper reaches are 2,300 paces on substructures or arches; while nearer the City, beginning at the seventh milestone, are 609 paces on substructures, 6,491 paces on arches. These are the highest arches, rising at certain points to 109 feet. With such an array of indispensable structures carrying so many waters, compare, if you will, the idle Pyramids or the useless, though famous, works of the Greeks!

Frontinus, 1st century AD [1]

The scientific content of this guide is under total responsibility of the authors

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Albano lake in 2002: pier for mooring boats built in the 1960s,
when the water level was higher than today
Photo by Walter Dragoni

INTRODUCTION

Before describing the stops of this Mid-Week Technical Field Trip, it appears appropriate to give some information about ancient Roman Technology.
Large scale rational management of water resources is one of the main characteristics of Roman civilization. This was well known since ancient times: as an example among many, we shall mention a sentence by Dionysius of Halicarnassus (ca. 60 BC – ca. 7 BC) "Indeed, in my opinion the three most magnificent works of Rome, in which the greatness of her empire is best seen, are the aqueducts, the paved roads and the construction of the sewers. I say this with respect not only to the usefulness of the work (concerning which I shall speak in the proper place), but also to the magnitude of the cost, …." [2].
Roman hydraulic technology has its roots in the Etruscan civilization [3, 4]. The Etruscan civilization, the development of which was strongly influenced by Greece and the Near East, flourished in Central Italy from about the 8th century BC onwards. Etruscans were masters of land reclamation and water management in general. As an example, Figure 1 shows an Etruscan tunnel, built in order to control the discharge of a small catchment close to the ancient Etruscan city of Veii, a few kilometers from Rome. After more than two thousand years the tunnel is still doing the job for which it was built.

Fig. 1 – The Etruscan Ponte Sodo, a tunnel about 75 m long. It is a good example of the Etruscan hydraulic technology; its main purpose appears to have been to control floods and reclaim land close to Veii, the Etruscan city located a few kilometers from Rome (photo by Walter Dragoni).

According to the tradition, accepted by the ancient Romans, Rome was founded in 753 BC. During its early history, Rome was ruled by Etruscan kings, the last of which was overthrown around the end of 6th century BC. The Etruscan kings transformed Rome into a true city, reclaiming swampy land between the hills and building the first sewers, of which the Cloaca Maxima (Greatest Sewer) is the best known. Etruscan rule, and the successive relations between the two ethnic groups, left to the Romans a patrimony of cultural and religious attitudes and rituals, as well as a sound knowledge of hydraulics and water management capability. By the first century BC, after a few centuries of turbulent relationships and wars, the Etruscans were absorbed by Rome (cf. e.g. [3, 4, 5]).
Roman hydraulic engineering and water management techniques, born out of the early achievements of Greece and Etruria, improved dramatically, going far beyond those of the predecessors and remaining unsurpassed until the end of the 18th century AD.

AQUEDUCTS

According to Sextus Julius Frontinus [1], the Roman consul who was named curator aquarum (guardian of the water) of Rome in 98 AD, Rome had nine aqueducts. Two hundred years later there were eleven, as two more were built in 109 and 226 AD [6]. The aqueducts of Rome, plus a few small local springs, supplied water to hundreds of public fountains and a few dozen monumental fountains and large private and public thermal baths, not counting the water supplied to the Imperial household and owners of private villas. Even in the fourth century, in a deep decline, Rome had 1352 fountains or cisterns [7]. The quantity of water and number of fountains in Rome was so large that the term Roma regina aquarum (Rome queen of the waters) has been commonly used since antiquity.
The attitude of ancient Rome towards water and fountains left a permanent imprint on Rome (and Italy), which survived the fall of the Roman Empire. Indeed, Rome is the city with the highest number of monumental and artistic fountains. This is reflected by the fact that even today there are more than one thousand little

fountains along the streets of Rome providing excellent free drinking water.
In Rome the first aqueduct was built in 312 BC. According to Frontinus, before that date Roman citizens had to use water from the river Tiber and from wells. In the 2nd century AD, the 11 aqueducts (Fig. 2) brought to Rome about 10 m^3/s of water (the exact figure is much questioned, being difficult to establish). There is a general agreement that at that time Rome had a population of between five hundred thousand and one million inhabitants: the water supplied by the aqueducts corresponded to the surprising amount of 800-1600 litres/day/person - much more than the amount available in most modern cities. This leads us to conclude that the amount of water brought to Rome was not necessary for the city's survival, but was essentially a cultural attitude [7].
The supply of such a huge quantity of water was, and still is, possible because the area in which Rome was founded is bordered to the north-west and south by volcanic hills with high precipitation. These hills also have various lakes and are rich in groundwater, giving rise to numerous springs. East of Rome, some dozen kilometres away, are the Central Apennines, limestone mountains which often reach 2000 metres in altitude.
They are snow-covered in winter, and their rainfall exceeds 1000 mm/year: large quantities of water recharge fractured and/or karstified aquifers. These underground waters are of exceptional drinking quality, and reach the surface through many high-discharge springs, some producing more than 10 m^3/s [7, 8, 9].

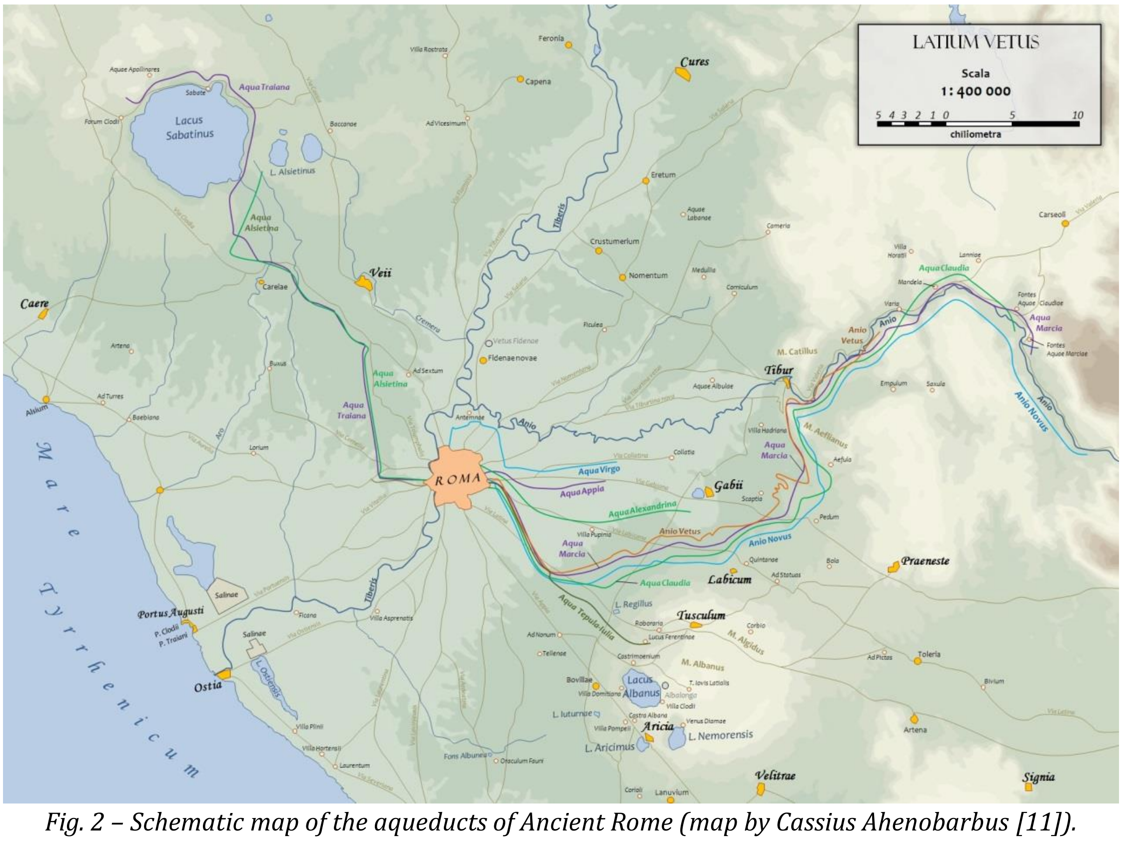

Fig. 2 – Schematic map of the aqueducts of Ancient Rome (map by Cassius Ahenobarbus [11]).

It is important to realize that the Roman Empire extended from the Spanish Atlantic coast to the Rhine River in Germany and the Black Sea, and from the Scottish Lowlands to a few hundred kilometers south of the North African Mediterranean coast [10]. In that large Empire, all Roman cities of any importance had a Forum (the business area), a theatre, an amphitheatre, military barracks, public baths and the necessary aqueducts and fountains to provide water for these structures and for the citizens [7].
Roman aqueducts could have a length up to more than one hundred kilometers: for example one of the aqueducts of Constantinople (presently Istanbul, in Turkey) had a length of ca. 250 km, while that of Gadara (Jordan) had a length of ca. 170 km [12].

To give an idea of the total number of Roman aqueducts all over the Empire, we shall mention that one of the many web sites dedicated to the issue reports a set of references regarding about 600 aqueducts [12]. Table 1 reports some data about the aqueducts supplying water to Rome, while Fig. 3 reports a general sketch of the main constituents of a Roman aqueduct.

DATE OF CONSTRUCTION	NAME	TOTAL LENGTH (km)
312 BC	Aqua Appia	17
272 BC	Anio Vetus	64
144 BC	Aqua Marcia	91
125 BC	Aqua Tepula	18
33 BC	Aqua Julia	23
19 BC	Aqua Virgo	19
2 BC	Aqua Alsietina	33
47 AD	Aqua Claudia	67
52 AD	Anio Novus	87
109 AD	Aqua Traiana	35
235 AD	Aqua Alexandrina	15

Table 1 - The aqueducts of Rome at the time of its maximum grandeur. The lengths are approximate, as in many cases the exact route is not known in its entirety and there are some uncertainties about the exact location of the water intake, which sometimes were multiple.

In Roman aqueducts, water flowed essentially in a free flowing canal; pressure flow was used only when it was the most efficient way to cross a deep valley: this because the pressure pipes were very costly; furthermore, for the technology of the time, it was not easy to make lead pipes able to bear high water pressure (for a detailed discussion about the issue, the reader is referred to [6, 13]). It has to be noted that Vitruvius (ca. 75 BC – 15 BC), in his well known engineering manual [14], describes a device to improve the efficiency and resistance of inverted siphons. Unfortunately the description by Vitruvius is unclear, mainly because he uses a word not used by any other Latin writer. The device appears to be a sort of "hydraulic tower" the purpose of which was, simplifying the issue, to dampen the vibrations of the structure and to dissipate pressure and kinetic energy. A few modern authors doubted that such devices existed in reality: however, recently, structures which fit the description of Vitruvius have been studied in the Aspendos aqueduct (in modern Southern Turkey, dated around 2nd - 3rd century AD).

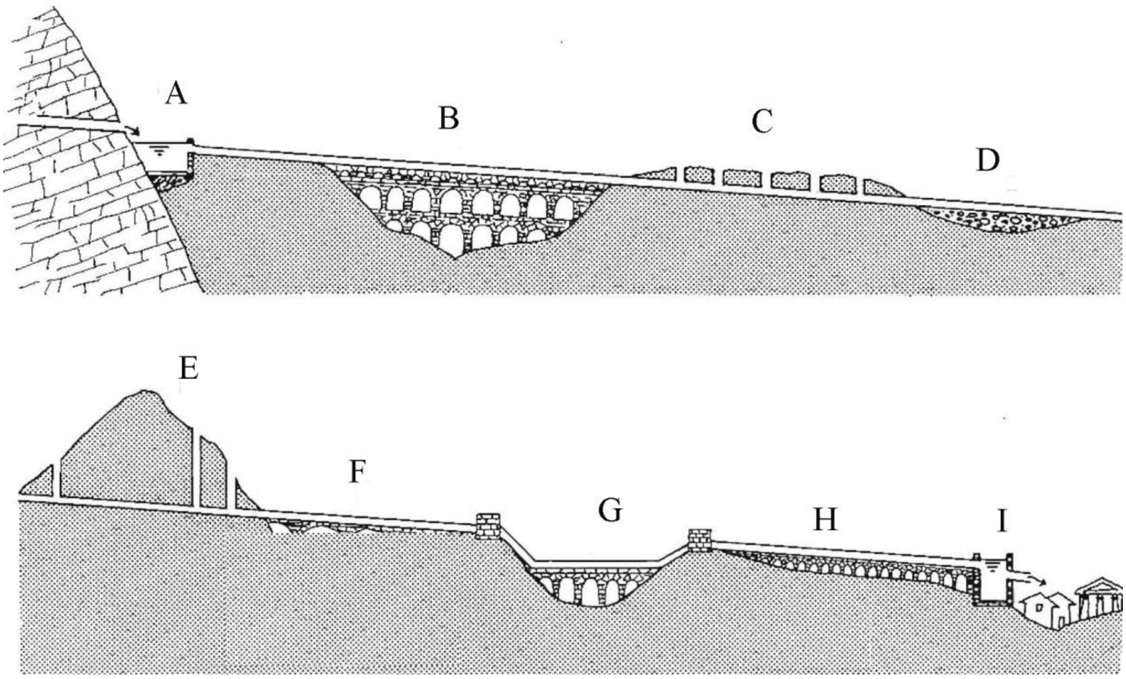

Fig. 3 – General sketch of the main constituents of a Roman aqueduct (partially redrawn after [3]).

A) Intake work: water could come from a spring, from one or more draining tunnels, or from a surface water body; usually the intake had a settling tank. B) Canal on a viaduct on multiple arcades. C) Shallow tunnel, dug by means of vertical shafts. D) Canal on top of an embankment. E) Tunnel at great depth, dug without or few vertical shafts. F) Canal on top of low arches/embankment. G) Inverted siphon; water flowed in pressure pipes. H) Final arcade, ending in a distribution tank (I).

The inverted siphon of Aspendos was studied and modelled according to the present hydraulic knowledge: the study shows that the Vitruvius structures are quite efficient [15]. Recent researches have also shown that Roman aqueducts were equipped with efficient drop-shafts, bypasses and intermediate reservoirs [16]: all these recent investigations indicate that the hydraulic knowledge embodied in the imperial aqueducts is much more advanced that hitherto thought [15, 16].

Figure 2 shows that the aqueducts of Rome have often a rather tortuous route (cf. those entering into the town from south-east). This is due to the necessity to maintain the aqueducts hydraulic gradient inside a proper range, so that the velocity of the water did not wear the canal and silting did not occur. Besides that, the gradient, and thus the route, had to be planned in such a way that water arrived to destination having an altitude compatible with a gravity distribution. In the specific case of Figure 2, the aqueducts entering the city from south-east, before reaching the flat Campagna Romana (Roman Countryside) followed the River Anio (today River Aniene), with a proper gradient. As described very clearly by Hodge [13], close to the city of Tibur (the modern Tivoli) the aqueducts "confronted an escarpment dropping abruptly 180 m to the Campagna below. .... The aqueducts ..... all swing south-west in a wide detour .... maintaining the same uniform gradient as they had in the Anio Valley". All over the Empire the "average" gradient of Roman aqueducts is around 0.3% - 1.5%, but values outside of this range are common [13]. In the aqueducts of Rome the average gradient is about 0.2%, but in some cases there are gradients between 0.021% and 3.4%, with a short segment of Anio Vetus having an exceptional value of 16.35% [6].

Finally, it is worth to mention that, in spite of sketch in Figure 3 and of the grandeur and visibility of the arcades, the main part of the ancient aqueducts is underground [16].

The decline of Rome brought about the inevitable deterioration of its aqueducts and fountains: the diminished population and, starting from the IV century AD, wars, the civic and economic situation and barbarian invasions made any kind of care or repair work almost impossible. The great aqueducts fell into ruins, due to a combination of natural wear, lack of maintenance, and the effects of several earthquakes. In addition, during sieges, assailants would break up the aqueducts in order to deprive the besieged citizens of water, and the latter would often wall them up, for fear the enemy would use them to enter the city.

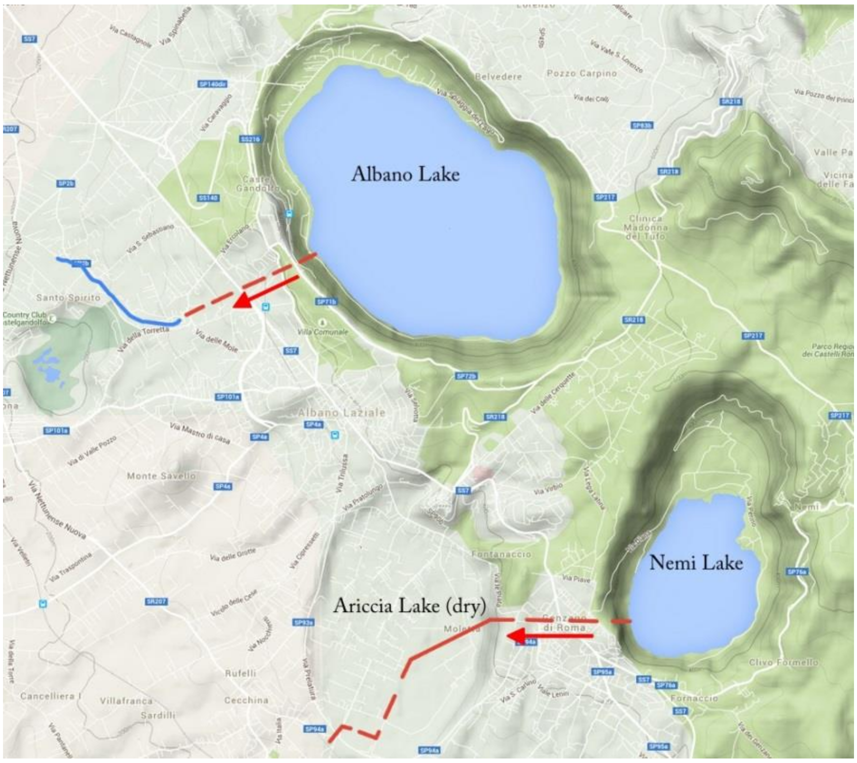

Fig. 4 – Lakes Albano, Nemi and Ariccia, the latter was dried up artificially in archaic times, probably during the 5^{th} century AD. The red lines indicate the emissaries (the dashed lines indicate the underground sections).

The important aspect here is that such complex aqueduct systems can only be built and function in a region which has achieved peace and is under the control of one centralised political power with substantial economic resources. In general, none of these requisites were met in Rome from the V to the XV centuries AD.

ANCIENT TUNNELS IN CENTRAL ITALY

Etruscans and Romans reclaimed swampy land and controlled the water oscillations of many closed lakes by means of underground canals [3, 13, 16, 17]. Table 2 reports a list of the most remarkable of these tunnels. Figure 4 shows Lakes Albano, Nemi and Ariccia, the latter entirely dried up by the ancient underground emissary.

UNDERGROUND OUTLET	LENGTH (M)	TIME OF CONSTRUCTION
Lake Ariccia	650	5th - 4th century BC (?)
Lake Nemi	1600	5th - 4th century BC (?)
Lake Albano	1400	Probably early 4th century BC
Lake Fucino	5595	52 AD

Table 2 – List of the most remarkable ancient tunnels for water control in Central Italy.

The Lakes Albano, Nemi and Ariccia are located on the volcanic Alban Hills, 20 km or so south-west of Rome. They occupy volcanic calderas. The Alban hills, about 1000 m above sea level, have been formed by intermittent eruptions from a large number of craters, active over about 600,000 years [18]. Until few years ago, there was agreement that the last strong volcanic activity in the area ended about 20.000 years ago, but recently this has been questioned, as some works, published in 2003 and 2005, claim that catastrophic events of volcanic origin occurred in the area in the 4th century. These events would be due to injections of CO_2 to the bottom of the Lake Albano, causing water surges above the rim of crater, with "significant mudflows" in the flat land outside the Alban Lake crater rim [18, 19]. According to these studies, the Alban tunnel was dug in order to lower the water level, aiming to minimize the effects of other possible water surges [18, 19]. However the issue is still open, as more recent research (published in 2009) appears to confirm the traditional view [20]. It is opinion of the writers that all the lake outlets in the area were dug in order to gain agriculture land, to manage irrigation and, possibly, for religious reasons: besides the Alban, Nemi and Ariccia Lakes, at least 10 other smaller volcanic lakes have been regulated by means of underground canals, obviously dug for reclamation purposes [17].

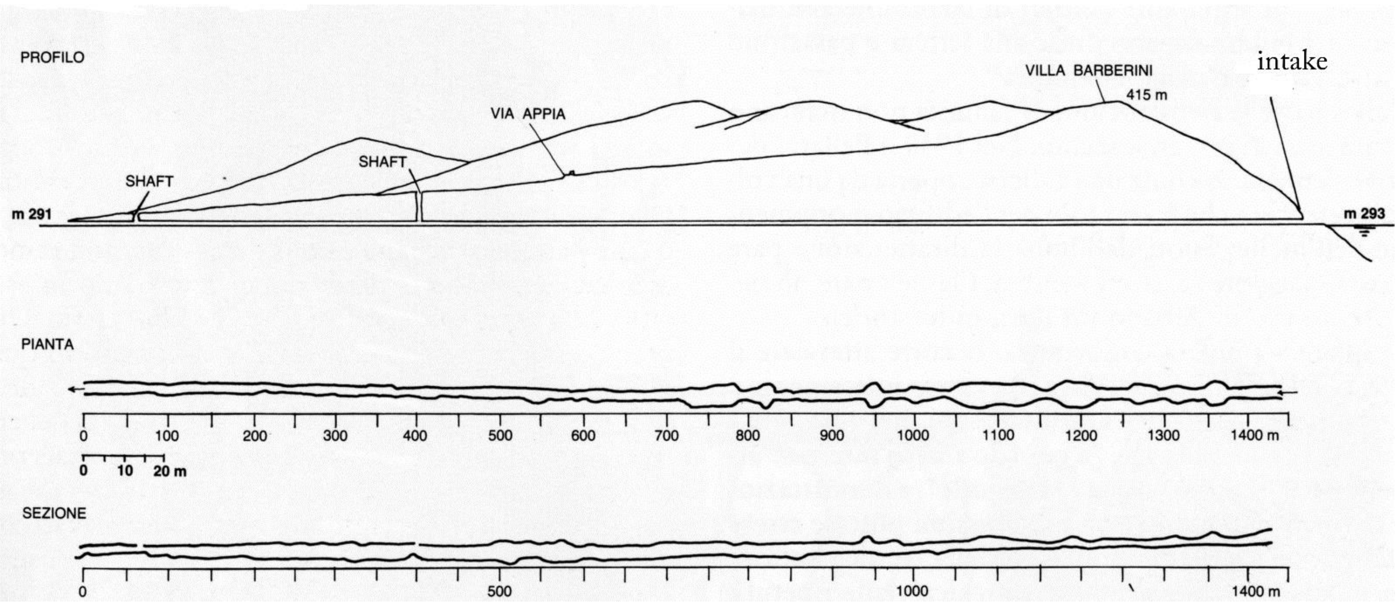

Fig. 5 – Sections of the Albano Tunnel [17].

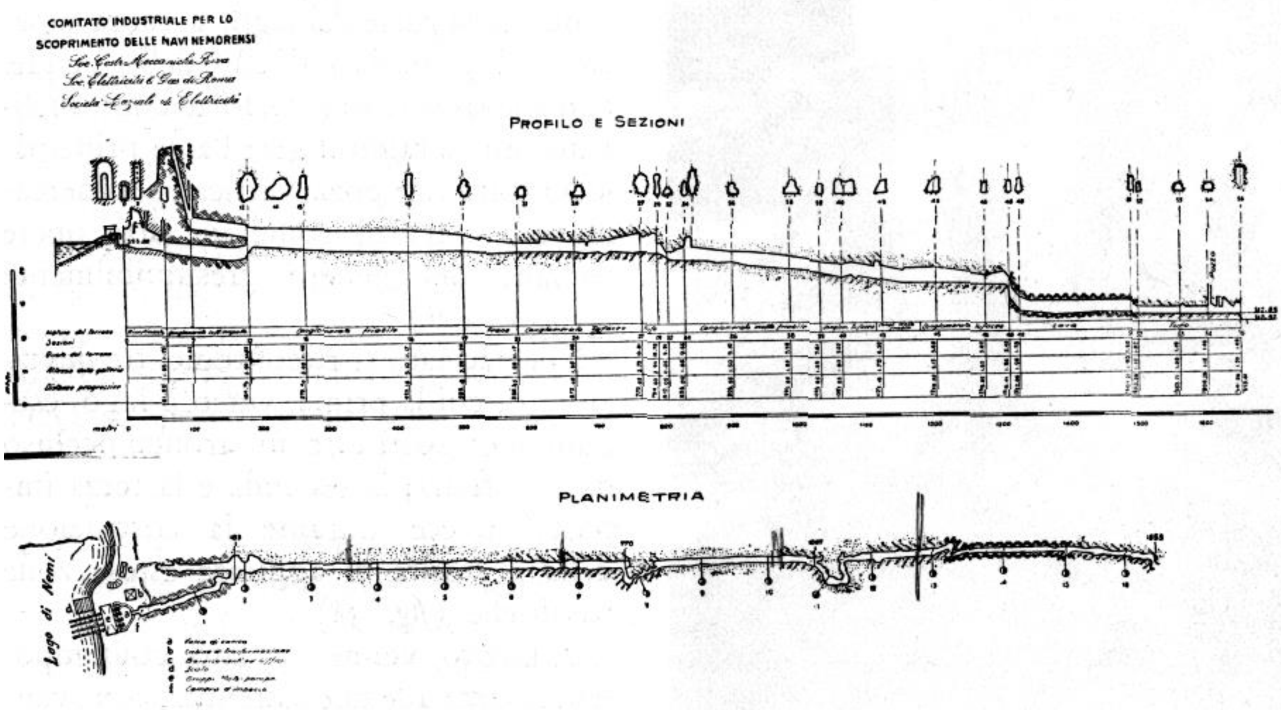

Fig. 6 – Section and plan of the Nemi Tunnel [17].

Figures 5 and 6 report a section of the tunnels of Lake Albano and Lake Nemi. It is important to note that the two tunnels were dug with very few vertical shafts, in a manner similar to that used in the Eupalinos tunnel (Samos, Greece) in the late 6th century BC [21]. An inspection of the tunnels shows that they were dug starting from the two opposite entrance. The hill crossed by the tunnels is made up by different kind of volcanic tuff (in general easy to dig) and lavas, much harder to dig, thus requiring, in general, longer time to advance. It is clear, especially in the Nemi tunnel, that the working teams had some difficulties to meet. More details about the two tunnels can be found, among others, in [17, 22, 23]. The Alban tunnel is the less known (it was crossed last time and mapped by tape and compass about five decades ago): at present it is not possible to walk the entire tunnel, as in many places piles of debris and water block the passage. Recently, the Egeria speleological group started a research work aiming to map it accurately and to clarify a few open questions about the planning and the building of the tunnel [24]. In this regard it may be of some interest to remark that in Central Italy, in spite of the archaeological researches carried out for centuries and the high density of urbanized areas, even today it is not too difficult to make new contributions to the body of knowledge regarding poorly known underground works or to make entirely new discoveries, as shown in [25]. Indeed, until a few decades ago, the main research interest was about the historic and artistic sides of the issue; at present, instead, research is focused on the technological evolution and, above all, on the environmental meaning of ancient hydraulic works (cf., just for example, [21, 26, 27]).

FIELD TRIP ITINERARY

Time	*Itinerary and Stops*
8, 00 - 9.00	From Sapienza University to the Park of Aqueducts;
9.00 - 10.00	Stop 1, Park of Aqueducts;
10.00 - 11.00	From Park of Aqueducts to Lake Nemi, Museo delle Navi (Museum of the Ships);
11.00 - 12.30	Visit of the Museum of the Ships and seminar about ancient tunnels in the area;
12.30 - 13.00	From Nemi Lake to restaurant “Il ramo d’oro” (The Golden Bough)
13.00 - 14.00	Lunch;
14.00 - 14.30	Group A) From the restaurant to Albano Lake;

Group B) From the restaurant to Albano Town;

14.30 - 16.00 Group A) Visit of monumental entrance of Albano Lake archaic tunnel;
Group B) Visit to the Great Roman Cistern of Albano;

14.30 - 16.00 Group B) Visit of monumental entrance of Albano Lake archaic tunnel;
Group A) Visit to the Great Roman Cistern of Albano;

16.00 - 18.00 Return to Sapienza University.

STOP 1 – PARK OF AQUEDUCTS

The Park of Aqueducts is an area of about 2.5 km^2 where the most important remains of the great aqueducts of Rome can be seen (Fig. 7). The area, which has survived the wild urbanization of recent decades, looks almost as it appeared in the 19th century, when artists from all over Europe came to Rome to paint the ruins and picturesque landscapes (cf., just for example Fig. 8).

Fig. 7 - Stop 1, Park of the Aqueducts (modified from Google Map).

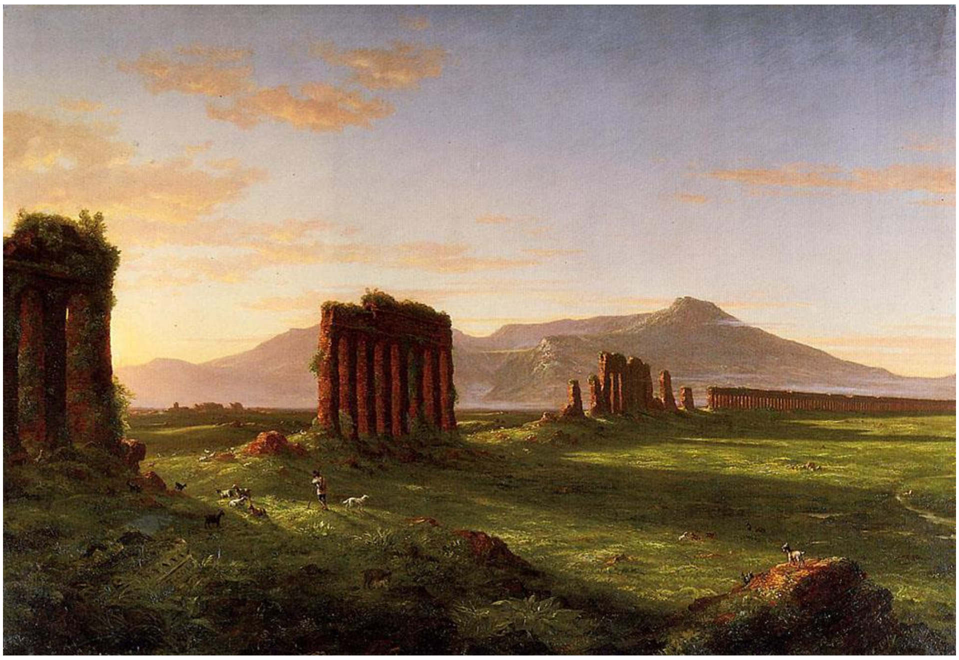

Fig. 8 - Roman Campagna (Roman Countryside), close to the Park of Aqueducts, by Cole Thomas, 1843, Wadsworth Atheneum. In the background it is possible to see the Alban Volcano (public domain image, [28]).

In the Park, the ruins of four aqueducts can be seen (Aqua Claudia, Anio Novus, Aqua Marcia and Aqua Felice).

The arcades of Aqua Claudia are particularly interesting, as they bear also the canal of Anio Novus (Fig. 9).

Fig. 9 - Arcades of Acqua Claudia. On top of the Claudia canal there is the canal of Anio Novus (photo by WD).

STOP 2 – NEMI LAKE AND MUSEUM OF THE SHIPS

The basin of Lake Nemi is an area of special value for its many environmental values, landscape, historical and archaeological sites, all the more remarkable in view of the proximity of the site to Rome, which is only 30 km away.

Figure 10 reports a view of the Lake.

Fig. 10 - Panoramic view of Nemi Lake (photo by WD).

The Lake is located in a caldera, and its waters mark the piezometric level of the regional aquifer. The Ships Museum is so called because between 1929 and 1932 two large Roman ships were recovered from the Lake. The Museum was established in 1935 in order to host permanently the two ships, which were destroyed at the end of the Second World War. There is an almost general agreement that the ships have been built by order of Emperor Caligula (37 - 41 AD). Today the Museum hosts two models of the ship and many archeological items of great value, together with some material regarding the ancient tunnel of Nemi Lake. Before visiting the museum, a short seminar will be given about the Alban tunnels and their relations to the climatic and hydrogeological evolution of the area.

STOP 3 – WATER INTAKE CHAMBER OF ALBAN LAKE TUNNEL

The Albano Lake is among the deepest lakes in Italy, being bout 170 m deep. As the Nemi Lake it has an ancient outlet tunnel, which controls the maximum height of the water level. The Nemi tunnel has a narrow upstream entrance and some features indicating that the original building plan was changed or not completed. The Albano tunnel, instead, has a monumental upstream entrance, which allows to make a few considerations about the way it was built and managed. During the last two decades the level of the Lake decreased, due to over pumping, and today the tunnel is dry [29]. The Figure on the cover of this guide (taken in 2002) shows a pier for mooring boats built in the 1960s, when the Lake level was much higher than today. Figure 11 reports a picture of the water intake chamber of the Albano tunnel.

Below the average present level of the lake (and about 6 - 7 m below the bottom of the Albano tunnel), there are remnants of a permanent settlement, the so called Villaggio delle Macine (Mills Village), dated ca. 18th - 16th BC [30]. Given that the tunnel was designed to carry water with a free surface, and that no pumps were available, it must be supposed that the elevation of the tunnel bottom is a few meters lower than what the lake's average level was when it was made. This means that between the 16th century BC and the 4th century BC the average level of the lake rose a few metres. This has been attributed to climatic variations [26] or to episodic uplifts and subsidences due to inflation and deflation of the central part of the volcano or to CO_2 accumulation creating a water surge [31].

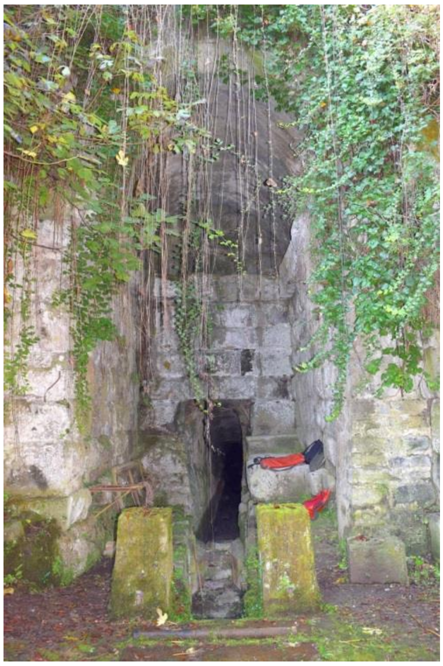

Fig. 11 - Upstream entrance of Albano Tunnel.

STOP 4 - CISTERNONE (GREAT CISTERN) OF ALBANO

At the end of the II century AD, Emperor Settimio Severo (146-211 AD) founded the Legio II Parthica and built a permanent fortified camp, known as Castra Albana, for hosting such Legio, made of 6000 legionaries. The legion remained in this is camp, which later originated the city of Albano, for about one century. In order to supply water to the 6000 legionaries Septimius Severus commissioned the construction of a large reservoir (today known as Cisternone or Cisternoni), capable of storing 10,000 m^3 of water.

The Cisternoni represented the wider water reservoir available to the Legio. Its position, on the upper part of the Camp, guaranteed an easy water distribution. The Cisternoni were used for drinking purposes up to 1912, while at present the municipality of Albano only uses it to water its public gardens.

The Cisternoni have a rectangular plan 1436,50 m^2 wide; they were dug 3-4 m deep in the Peperino pyroclastic complex, leaving 36 pillars which divide the building in 5 naves. Such pillars support the brick arches which hold the barrel

vault. The water supply is guaranteed to the reservoir by two aqueducts, recently studied by [32, 33, 35]. The oldest one, is known as the Acquedotto delle Cento Bocche (One Hundred Mouths Aqueduct). According to Lugli [34] it dates to the period of the Claudii – at the beginning of the 1st Century AD, so that it is older than the Cisternoni. It collects extremely small amounts of seepage water, over the distance of 150 m, between Palazzolo and Malafitto.
The spring area is located on the western slope of the Albano Lake, in the gully at Ponte di Nemi. The presence of small permanent springs in this and other areas of the Albano crater is typically due the fact that the volcanic edifice is alternatively built with different materials: pyroclastic flows, lava flows and tuff products in general, each having a different permeability. After covering around 3 km from the spring along the Albano crater, the "Cento Bocche Aqueduct" reaches Colle dei Cappuccini and, after forming a sharp right-angle bend, it runs underground in a semi-circle beneath the hill for half a kilometer. It presently ends up on piazza San Paolo in Albano; its original endpoint is not known.
From the same spring area in the gully of Ponte di Nemi two more aqueducts start. They are known as Malafitto Alto and Malafitto Basso. The Malafitto Alto aqueduct, dated back to the times of Domitian, mainly supplied water to the Domitian's villa. A secondary branch of this aqueduct represents the second supply of the Cisternoni, running into the reservoir at the end of the second nave.

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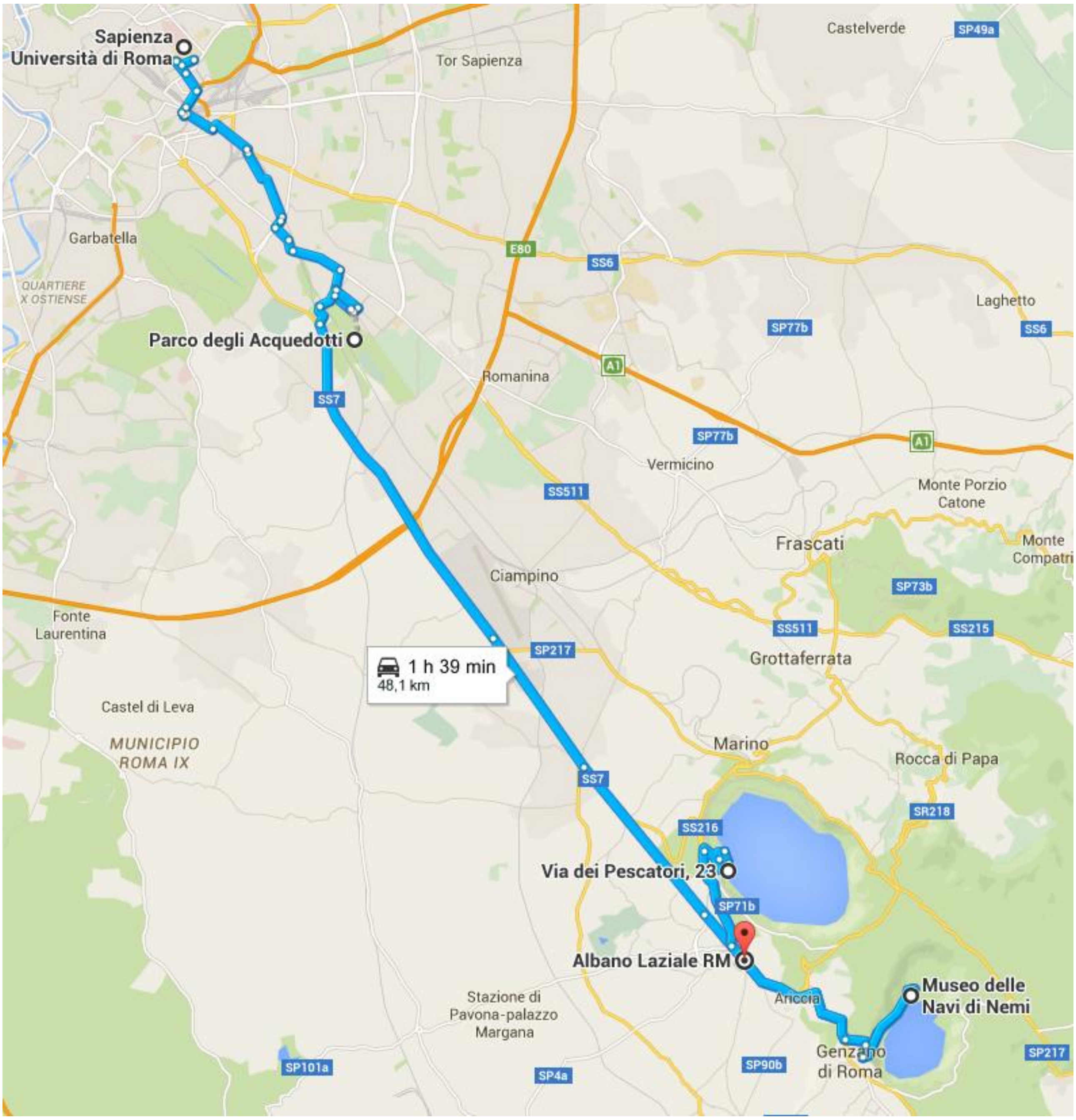

Route of MT1 Field Trip.