# Water supply of Bologna (Italy) by Roman aqueduct: history, morphology and hydraulic, from ancient time to nowadays

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## ABSTRACT

A brief description of the geomorphological, historical, and archaeological aspects of the ancient Bononia (now Bologna) supply by means of an ancient tunnel made by Romans at the beginning of the new, era and its evolution to a nowadays when it's already used (13%) to assure drinking water supply of Bologna Town. Recent exploration of the tunnel has permitted to obtain most data of ancient water level signs and size of tunnel section in the different conditions. New data obtained by this exploration allow to build a CAD 3D model of the tunnel and in this way it was possible to calculate the realistic flow of the ancient tunnel. Mathematical model simulations indicate the effectiveness of the ancient tunnel in achieving these objectives in working condition and during the periodical maintenance.

**Key words** | ancient tunnel, Bologna water supply, Bononia aqueduct, channel water flow simulation, speleology

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## INTRODUCTION

Bologna (Latin name Bononia) has always played an important role owing to its geographic position which makes it a natural crossroads and transition point for people and goods moving along the North-South and East-West axes.

Already important at the time of the Etruscans (who called it Felsina) who governed the city for nearly two centuries, towards the mid 4th century B.C. it began to decline as a result of the invasion of the Galli Boii, who descended from the North.

In the year 191 B.C., the Roman army led by Publius Cornelius Scipio Nasica defeated the Gauls and conquered Bologna and the entire region. A Latin colony was found founded with 2–3 thousand inhabitants which then merged with the preceding population of Villanovian-Etruscan origin. It then took the name of Bononia and a new phase of expansion began. The strategic importance of the city was enhanced by the construction of the Via Emilia which was completed a few years later (187 B.C) and was designed to facilitate the movement of the legions having the task of controlling points of critical importance for security and well as commercial traffic with northern Italy and central Europe (Figure 1).

Roman aqueduct of Bononia: growth and decline By the year 30 B.C. Bononia had become so important that it was now necessary to provide its inhabitants with infrastructures and services such as theatres, fountains, Baths, etc. typical features of the capital, Rome. The water supplies of Bononia could no longer be guaranteed by springs and cisterns alone. In order to have high quality water and a suitable piezometric height which the river Reno, running quite near to the city, was no able to guarantee, the city authorities turned to the clear water of the Setta stream, a tributary of the Reno flowing South of the city.

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**Figure 1** | Bononia and Via Aemilia.

Caesar Octavianus, who had now become emperor (Augustus), promoted the construction of important public works, such as the aqueduct, which was thus given the name of Augustan aqueduct. In view of the nature of the substratum involved, mainly consisting of clay and sandstone, as well as of the features of the terrain, a 19.7 Km tunnel (average slope is 1,5‰) was dug under the Bologna hills to convey the drinking water required to the city (Figure 2).

The technique used to construct the tunnel, as described in the treatises of Frontinus and Vetruvius, was based on the well-known system of intermediate wells and of teams of labourers advancing from opposite directions along the proposed tunnel. The aqueduct indeed underwent successive restorations during the periods of Adrianus and Septimius Severus and was used until the beginning of the Middle Ages when, after repeated barbarian invasions, natural disasters, etc. it ceased to function. As a result of the complete absence of written plans but above all of infrastructures visible from the exterior (except for the inspection apertures which caved in and were overgrown by vegetation), its historical memory was lost for nearly one thousand five hundred years, until the end of the 17th century, when a series of finds, accidental at first and then increasingly systematic, allowed the ancient tunnel to be rediscovered and explored.

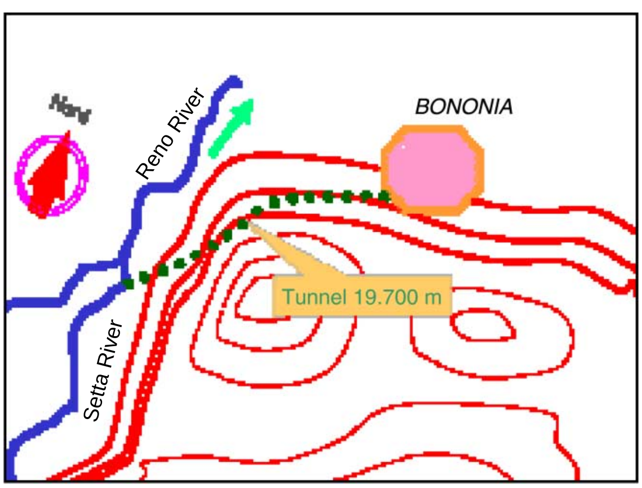


**Figure 2** | Path of the ancient aqueduct.

Throughout this long period of time, drinking water supplies to the city were guaranteed, as during the Etruscan period, by springs in the vicinity of the urban area, and by cisterns and shallow wells.

However, these sources of supply, in particular the wells serving the buildings in the urban area, were anything but safe from the point of view of hygiene so that cholera epidemics were a constant scourge afflicting the city until the late 19th century (Del Panta 1980). In a census of municipalities were founded over 14.500 wells with a population of 120.000 inhabitants (Bellettini & Tassinari 1977).

## REDISCOVERING OF ANCIENT ROMAN AQUEDUCT

This situation was no longer tolerable, especially after the establishment of the new unified State (Italy was reunited in 1861). The young state set out to overcome the chronic lack of infrastructures, one of the causes of the disastrous health and hygiene situation, which had been inherited from the Church State to which Bologna belonged before national reunification.

The rediscovery of the ancient aqueduct and the need to overcome the health and hygiene emergency as quickly as possible led the city's authorities to reinstate the tunnel and again to utilize the water from the Setta stream. Owing to the limited human presence and industrial activities the latter had maintained an excellent water quality. This quality was further guaranteed by the construction (among the first in Italy) of a filtering tunnel (Figures 3 and 4) under the stream bed. This simple treatment allowed the water to be used even under conditions of turbidity which occasionally occurred, particularly after heavy rain, owing to the partly clayey nature of the soil in the catchment area.

Fundamental work was done by the archaeologist and engineer Antonio Zannoni who successfully combined a passion for archaeological research (he made the first survey of the aqueduct) with his job as a functionary of Bologna municipality charged with solving the problem of how to supply the city with water. Zannoni began his first inspection of the ancient aqueduct in 1862, and in 1868 he finalized a recovery project (except for a few sections that could no longer be used) including intake and final distribution works (Zannoni 1868). The construction and management (for a period of 50 years) was contracted out to an Italian firm with Swiss and German capital in 1874 and on 5 June 1881 the new-ancient aqueduct was reopened.

The benefits accruing to public health emerged however only after 1886, the year in which, following an outbreak of cholera (Giusberti *et al.* 1999) in which 400 people died, the mayor took the necessary administrative and technical steps (more fountains) to curb the use of wells. Up until then the majority of the population used wells as the water could be drawn from them gratis.

Currently drinking water supplies to the city of Bologna amount to some 86 million $m^3$ per year and are guaranteed by multiple sources; the contribution of the ancient aqueduct, which has a mean flow rate of 350 l/s accounts for about 13% of requirements.

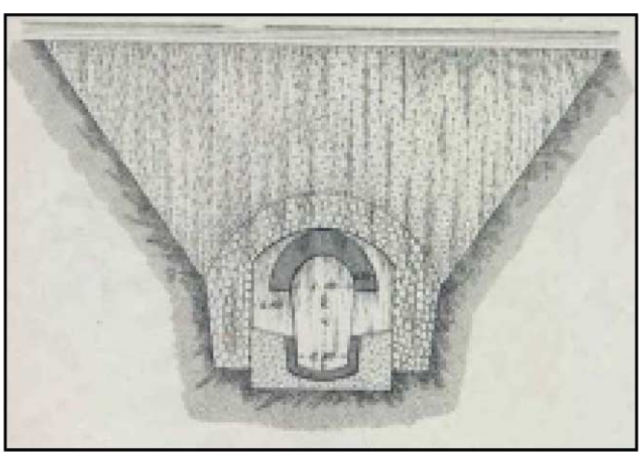

**Figure 3** | Drawing of filtering tunnel (Zannoni 1868).

**Figure 4** | Picture inside the filtering tunnel (picture by Renato Drusiani, 2006).

## THE LATEST INSPECTIONS AND SURVEYS OF THE ROMAN TUNNEL

Over the years inspections have been carried out in the course of maintenance operations which it has been possible to exploit also for research purposes. One significant inspection was the one organized in the mid 1980s which led to the discovery of interesting pictograms illustrating the way the construction site had been organized (AA.VV. 1985).

In 2005, following the closing of the tunnel for scheduled maintenance, HERA, the company managing the aqueduct, deemed it of interest to avail itself of the expertise and skills of experts in the field of speleological exploration, in particular those of Gruppo Speleologico Bolognese - Unione Speleologica Bolognese (GSB USB) in order to make a complete survey of the installation. This time modern computer-based instruments backed up by multilayer CAD support were used to correct and update the previous survey dating back to the 19th century. The survey campaign lasted two months and produced further morphological and structural data pertaining to the ancient installation which would allow a more accurate estimate to be made of the water transport capacity of the tunnel.

An ad hoc map base was created on a CAD support using the1:5.000 scale Regional Technical Map, adequately supplemented by other more detailed maps (Bologna Municipality and HERA). On this basic map all the

**Table 1** | Example of geometric data observed for the Roman Tunnel sections

| Datum point Num. | Width (cm) | Height (cm) | Section shape | Materials of walls | Materials of vault |
|---|---|---|---|---|---|
| C50 | 65 | 225 | Fusoid | Concretions | Dug out of rock + concretions |
| C51 | 60 | 222 | Fusoid | Concretions | Dug out of rock + concretions |
| C52 | 65 | 206 | Arch | Concretions | Dug out of rock + concretions |
| C53 | 65 | 210 | Arch | Concretions | Dug out of rock + concretions |
| C54 | 50 | 170 | Arch | Dug out of rock | Dug out of rock |

entrances were georeferenced and the entire layout of the facility was mapped, including the sections of the Roman aqueduct that had been by-passed and were now no longer in use.

An accurate altimeter readings then allowed the longitudinal section of the entire complex to be mapped, together with the altimetric profile of the slopes under which the hypogeal aqueduct flows.

For each station point inside the water main (a total of about 1,200) the transversal section was then surveyed, with reference to well-defined construction standards, as well as to the size and materials used to construct the walls and vault, as shown in Table 1. Each of these points was also documented photographically (Figure 5).

The survey was completed with the architectural drawings of the entrance points (towers for the wells and access manholes for the horizontal tunnels, etc.), all of which accompanied by a collection of documents and a bibliography of publications referring to the aqueduct, covering a time span of five centuries.

This inspection and survey activity illustrates the tortuous nature of the underground tunnel designed to follow as far as possible the course of the Reno river as well as to ensure that it always remained below ground level even in the presence of obstacles that required it be lengthened in order to avoid them. The tunnel was also adapted to the various geological situations: in the presence of sandstones with a strong resistance the tunnel was dug directly out of the bare rock while substantial lining with wall thicknesses varying from 50 to 60 cm when clayey or marnous soils were crossed. In marnous zones, the lining was made of blocks of the same rocks as those found in situ, while in clayey soils bricks were prevalently used. In the restructuring carried out in the late 19th century, because of the conditions of instability due to the presence of clay in certain areas, part of the tunnel was completely rebuilt using the typical ovoidal shaped section widely used in hydraulic works (aqueducts and sewers) typical of that period.

## HYDRAULIC MODELLING OF THE ROMAN TUNNEL

In order to determine the flow rate inside the Roman Tunnel during the period of its full functioning (roughly from 30 B.C, to the 4th century A.D.), the mathematical model of the entire hydraulic installation was made using Infoworks CS 9.5 (IWCS) hydraulic modelling software produced by the British company Wallingford Software Ltd, which is generally used for urban drainage networks.

Above all it was necessary to input the geometric and plano-altimetric data referring to the tunnel which had been

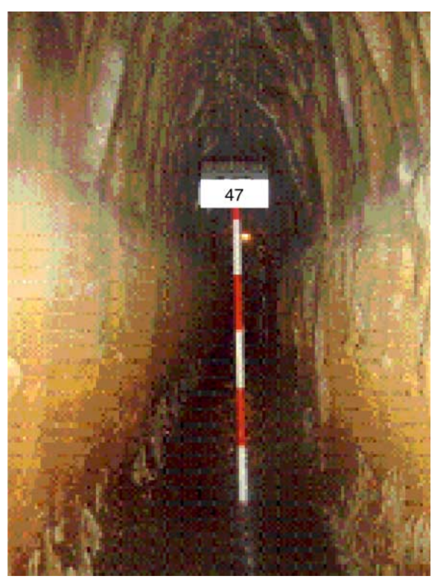


**Figure 5** | Section with datum point (picture by GSB USB, year 2005).

obtained from recent surveys. The data were available in AutoCAD DWG format as far as the tunnel path and the profile are concerned and in tabular form for the section geometries. The DWG file of the tunnel has been georeferenced in the UTM reference system.

Once the geometric/morphological characteristics of the section set out in Table 1 has been input, the software calculates the dimensions of the whole section and, on the basis of the height of the bottom, also defines the longitudinal trend.

The artifacts along the tunnel were modelled, in particular making provision, in the presence of sluice's groove on the side walls, for the insertion of the relative sluice gates while in the tunnel curves concentrated load losses that were of an intensity proportional to the amplitude of the angle.

The software allows different formulae to be selected to calculate the motion; it was decided to use Manning's formula, inserting a value of 0.018 s/m1/3 for the exponent n. This was done considering the materials constituting the walls and the vault of the tunnel when it was built. Also taking into account the almost constant minimum of one per thousand, motion is always considered in slow flow mode ($Fr < 1$).

## SIMULATIONS PERFORMED

Normally, once a model has been implemented, it is attempted to validate it hydraulically using a historical series of flow rate and level measures, something that is obviously not possible in the present case as the aim was to simulate the ancient path of the tunnel and not that used today including the modifications made in the path in accordance with Zannoni's project.

The only data that can be used to calibrate the model is therefore the level of the lime incrustations observed by the speleologists in the ancient sections currently no longer in use, equatable with the mean value of the water height In particular, the height of the incrustations observed in the section in the vicinity Bocca Rio Conco was used, which measured 1.5–1.6 m (Figure 6).

Several simulations were therefore carried in a permanent flow regime varying the intake flowrate at the initial node of the tunnel. The results show that the flowrate generating a level of 1.5–1.6 m in the Rio Conco d calibration section, is 0.55–0.56 $m^3$/s, with a mean velocity of about 0.59 m/s.

**Figure 6** | Tunnel near Rio Conco (pictures by GSB USB, 2005).

The model also enabled it to be ascertained that with flowrates exceeding 0.6 $m^3$/s the tunnel has the inner surface completely wet including the calibration section.

Converting the International System unit of flowrate measurement into that used in ancient Rome, namely the *quinaria* (1 quinaria = 0.48 l/s) it may be said that the mean flowrate in the Roman tunnel at the time of its peak functioning may be estimated as 0.55–0.56 $m^3$/s which gives 47,000–48,000 cm/day corresponding to 1,150–1,160 quinarias. Figure 7 shows the hydraulic profile and Table 2 the corresponding numerical results referring to the section used for calibration.

The differences in section shape and in their size, albeit only slight, are cause of variations in level along the tunnel. Nevertheless the mean value of the hydraulic head in the Roman tunnel is found to be 1.6–1.7 m, with a standard deviation of ±0.36 m.

The above simulations refer to normal functioning with the discharge tunnels closed. It was thus hypothesized to discharge the water laterally raising the sluice gate, a condition that obtains when maintenance/cleaning of the tunnel is carried out. In this case it was ascertained that, the intake flowrate remaining equal, the water velocity

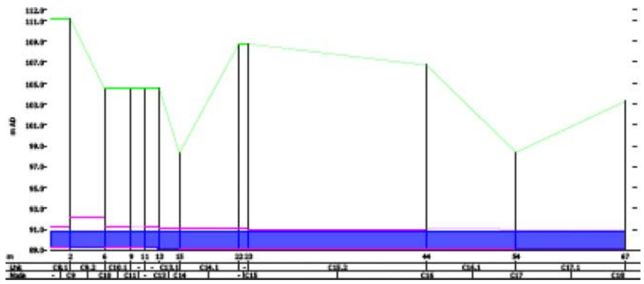

**Figure 7** | Hydraulic profile of tunnel corresponding to Bocca Rio Conco ($Q = 0.558\,m^3/s$).

**Table 2** | Simulation results ($Q = 0.558\,m^3/s$) for the tunnel stretch near Bocca Rio Conco

| Datum point Num. | Head (m) | $Q$ ($m^3/s$) | N. Fr | Vel. (m/s) |
|---|---|---|---|---|
| Bocca Rio Conco 2 | 1.594 | 0.558 | 0.144 | 0.585 |
| C10 | 1.486 | 0.558 | 0.140 | 0.536 |
| C11 | 1.518 | 0.558 | 0.135 | 0.525 |
| C12 | 1.553 | 0.558 | 0.136 | 0.537 |
| C13 | 1.599 | 0.558 | 0.147 | 0.598 |
| C14 | 1.595 | 0.558 | 0.144 | 0.584 |
| C15 | 1.580 | 0.558 | 0.142 | 0.581 |
| C16 | 1.611 | 0.558 | 0.152 | 0.633 |
| C17 | 1.650 | 0.558 | 0.139 | 0.599 |
| C9 | 1.478 | 0.558 | 0.142 | 0.539 |

upstream from the discharge can even exceed 1 m/s, which is enough to remove the finer particles settling in the tunnel.

## CONSIDERATION OF THE RESULTS OBTAINED

If we consider that the gross quantity of water available to a Roman citizen during the imperial period may be estimated as about 1.5 cm/day (Pace 2006) it might be concluded that the tunnel serving Bononia, when operating at its maximum capacity of 48,000 cm/d, could cater to a population of up to 32,000 measured by the standards of the capital. However, this population estimate is purely indicative and cannot be considered as reliable evidence, for a number of reasons.

Firstly, it would be necessary to refer to the minimum flowrate that can be withdrawn from the watercourse. In this connection, Zannoni himself (Giusberti *et al.* 1999) in estimating the water withdrawable from the Setta torrent took its flowrate as (240 l/s, as inferred from the functioning of a water mill (Albano mill) near the intake.

Unlike the other water transport works (e.g. canals on arches) in which it was possible to a certain extent to “size” the flow section, in the case of the underground tunnel in question, its section corresponded to the minimum size that would allow the tunnel digger using manual techniques to advance. Oversizing was inevitable, but also useful, if we consider the storage function allowed by the sluices, the traces of whose housing still remain, that allowed the water level to be kept constant under various flow conditions, as attested by the incrustations.

For the purpose of cleaning the tunnel, a verification was also made of the functionality of the systems of discharges situated along the tunnel operated by opening the sluices. In this connection it is considered that the numerous side tunnels, practically all of which had overflow levels, might have had the dual function of maintaining water pressure in some sections of the tunnel or for the purpose of flushing and thus cleaning the tunnel.

## CONCLUSIONS

The foregoing represents an initial treatment illustrating and using the observations and analyses emerging from the complete speleological inspection made of the whole tunnel, which was completed in 2006. Further detailed studies are under way based on the elements so far collected. It is however the results illustrated herein, based on what may be considered the most complete and faithful model of the ancient tunnel, may be considered particularly significant. On the other hand, this gradual increase in our knowledge of the Augustan aqueduct is also of use in gaining greater insight in the installation, its characteristics and performance, and also for the purpose of implementing the best maintenance policies. Even though the old tunnel for years has no longer formed an essential part of the city of Bologna water supply system, the fact of keeping it in service, as well as saving energy compared with conventional systems, as a result of the maintenance policies adopted represents a guarantee against possible degradation and further obsolescence of the old tunnel.

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