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Original article

A rainfall data analysis for the archeological drawing of the Augustan aqueduct route

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ABSTRACT

Was *Cumae* supplied by the collection of rainwater, widely practiced for long time in the Mediterranean area, or by a branch of the Augustan Aqueduct? The main goal of *Aqua Augusta* was to provide water to *Puteoli* (civilian) and *Misenum* (military) that were two of the main harbors of the Empire. However, the ruins of the branch that would have flowed through *Cumae* have not been excavated yet. The aqueduct structure has not been studied in detail due to the difficulty in inspecting and the missing arches. A rainfall data analysis was carried out to assess the flow and use of the water conveyed by the *Aqua Augusta* aqueduct to *Cumae*. Results indicated that rainwater was not sufficient to supply *Cumae* and the *Aqua Augusta* should have played a great role in delivering water to the city.

1. Introduction

Traditionally, the archaeology of water has been formerly focused on the aesthetic and architectural features of hydraulic works rather than on technical and mechanical aspects [1]. Over the centuries, civilizations developed structures to bring drinking water to the population centers, especially through the use of aqueducts. There are many historical records on the purpose and design of aqueducts. Many of these aqueducts, though thousands of years old, are still standing [2]. Although the crucial importance of water is well known, water supply has not been considered as particularly interesting [3–5]. The great bridges constitute an exception like the long arcades of Roman aqueducts, which continue to enrich the landscape of countryside and cities all around Europe (e.g. Pont-du-Gard, France). Surprisingly, engineering and aesthetic issues were always effectively conjugated. Whenever possible Roman engineers followed, the steady downhill course at/or belowground level for constructing aqueducts [6–9]. Rome's aqueduct system was underground by approximately 87% [3]. Many of these sections were deep tunneled through limestone and tufa rock. Others were excavated into the hillside with an engineered rock and mortar tunnel set into the excavation and then backfilled with the native soil [10–12]. Thus, the study of their routes is not an easy task to carry out, as in the case of the double-branched Augustan Aqueduct (*Aqua Augusta*) built in Campania Region between 20 and 30 AD [13]. The former branch gushed from the spring of *Serino* located in the *Terminio-Tuoro* Mountain taking water up to Benevento. The other branch originated at "*Acquaro-Pelosi*", still from *Serino* spring, feeding *Misenum* [11]. The former and almost entirely underground branch was 103 km long having many secondary branches being 60 km long. A section of *Aqua Augusta*, the longest aqueduct of the Roman Empire [12], was brought to light in February 2012 by a landslide occurred after a heavy snowfall [14]. The first historical survey of its open-air route and the deep-tunneled sections was carried out by Abate [15] in order to assess the possibility of using the ancient tunnels for a new aqueduct supplying the City of Naples. Nowadays, the study of the original route of the aqueduct cannot be considered concluded. Unfortunately, the *Aqua Augusta* has not been sufficiently investigated for the following reasons:

- the structure is mostly underground and inspections are difficult;
- it is not considered of architectural interest.

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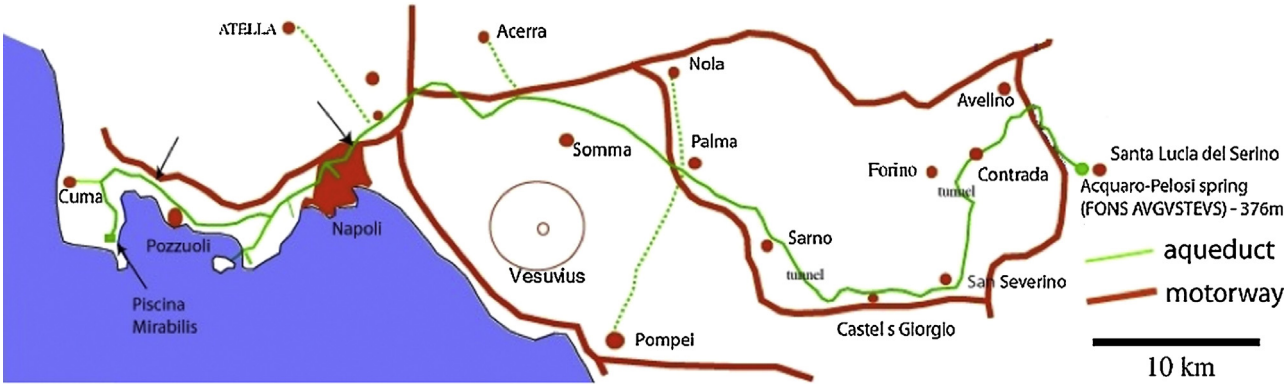

Fig. 1. Location of Cumae along the route of the Augustan aqueduct from Serino to Miseno.

Adopted from De Feo et al. [31].

An inscription, attesting its repair at the time of Constantine the Great (324/326 AD), indicated that the aqueduct served the cities of *Puteoli*, *Neapolis*, *Nola*, *Atella*, *Cumae*, *Acerrae*, *Baia Misenum* and the coastal cities of *Vesuvius* (*Pompei* and *Hercolanum*). The ruins of this branch flowing through *Cumae* have not been excavated yet, so there is no real proof of its route [11].

Cumae (*Cuma* archeological site, No.40.848356, E 14.054078) is located on the northern edge of *Campi Flegrei* (Naples, Campania Region, Italy), facing south and parallel to the Domitian coast (Fig. 1).

The settlement was established by Greek colonists in the VIII Century BCE, sacked by Oscans in the V Century BCE and incorporated into the Roman Empire in the IV Century BCE [16]. Nowadays, the most celebrated site at *Cumae* is the Sybil's Cave, the Archaeological Park houses, a series of ancient ruins and artefacts, including two Roman baths and various tunnels and cisterns. Baths were popular places of mass resort and the first sanitary facilities, being standard equipment in modern houses, but they were often not included in ancient roman dwellings. The main scope of Roman aqueducts was to fed baths continually [3]. Manderscheid [7] assumed that since the thermal baths were located outside cities, accomodations for housing and feeding patients must have been furnished. According to him, since the relative temperatures of the springs vary considerably between 26 °C and 70 °C, there must have been some provisions for cooling the water down to a temperature which was beneficial or perhaps comfortable to the human body. Indeed, in only a very few cases would the water have automatically cooled off sufficiently on its way from the source to the bathing pools. The archeology evidence reveals two possibilities:

- an installation of cooling into which the water would flow before being introduced into the *piscinae*;
- the mixing of hot thermal water with fresh water which have must been transported separately over a relatively long distance by means of an aqueduct.

The use of cisterns was very common in roman baths [17]. For instance, in the Baths of Caracalla (Rome), water was supplied by the *Aqua Nova Antoniniana* and *Aqua Marcia* aqueducts and local springs and stored in 18 cisterns uring bath time, people gathered daily their social life in an informal context drinking wine and having sexual relationships. Despite the eventual moral disapproval, the popularity of baths endured for over a millennium and spread all over the Roman time [18,19].

The aim of this paper is to investigate the hypothesis that rainwater was not the only water source for *Cumae*. A statistical analysis of rainfall data was carried out over a 2000-year period estimating the water demand in *Cumae*. The analysis considered that between I - II Centuries AD *Cumae* experienced an increased water demand due to a great economic, cultural and social growth. Based on the relief of the Cumae *Forum* bath operated by the authors, two fundamental hypothesis about *Cumae* water supply system were assessed:

- the collection of rainwater, which had been practiced for long time in the Mediterranean area [19–21];
- the historical records of a branch of the Augustan Aqueduct, which would have reached the city [22].

2. Methodological approach

In order to determine whether the forum cistern was supplied with rainwater, the average annual rainfall in *Cumae* was inferred in the I Century AD using hydrological data from the 1916–1999 annals assuming temporal recurring rainfall events. De Martino et al. [23] supplied further data for the period 2000–2006. There are no data available before 1916. The rainfall stations chosen for the analysis were located along the border of *Cumae* that is *Pozzuoli*, Naples *Capodimonte* (Observatory), *Camaldoli* (Hermitage), *Ischia* (*Forio*) or *Ischia* (*Porto*) and *Licola*. Rainfall events ranged between 408 mm (1957) and 1383 mm (1979).

Due to the complexity of the monthly rainfall analysis and lack of historical data, rainfall estimation was worked out using the value of the average rainfalls inferred by an exponential smoothing state space model starting from the average annual rainfall between 1916 and 2006. This model used a three-character string identifying the framework terminology of Hyndman and Khandakar [24] through R package forecast. By using ZZZ as default values, the model automatically selected the best model (Additive or Multiplicative) for the error, trend and seasonality of the rainfall series. Two automatic forecasting algorithms were implemented in the forecast package for R [24]. The first one is based on the innovation state space models that underlie exponential smoothing methods. The second is a step-wise forecasting algorithm with Autoregressive integrated moving average (ARIMA) model that is a generalization of an autoregressive moving average (ARMA) model. These models are fitted to time series data either to better understand the data or to predict future points in the series (forecasting).

The algorithms are applicable to both seasonal and non-seasonal data. In order to obtain a robust and widely applicable automatic forecasting algorithm, we followed the following steps:

- application of all models for each series optimizing the parameters (both smoothing parameters and the initial state variable) of the model in each case;

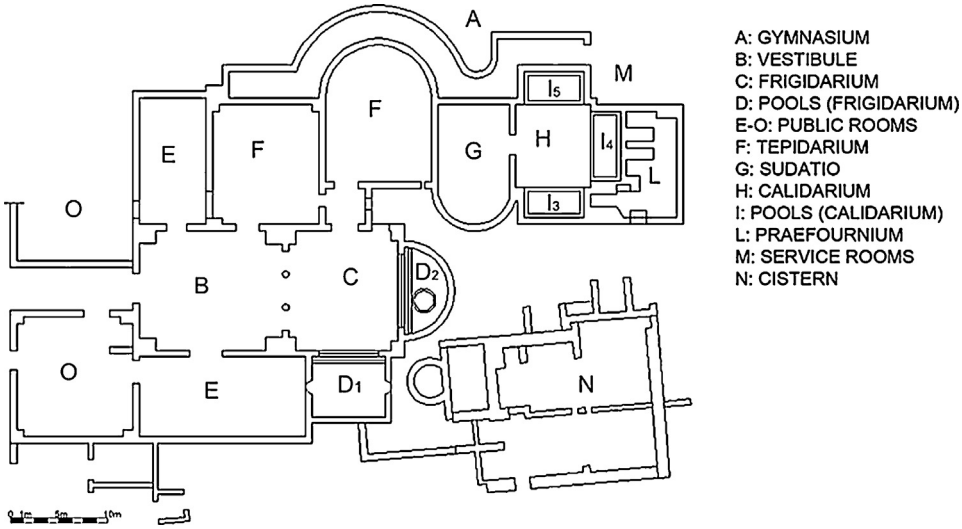

Fig. 2. Topographic survey of forum bath.

- selection of the best model according to the Akaike's information criterion, a measure of the relative quality of statistical models for a given set of data;
- point forecasting using the best model (with optimized parameters) for as many steps ahead as required;
- obtain the prediction intervals for the best model either simulating future sample paths using the normal distribution for errors (parametric bootstrap that is the practice of estimating properties of an estimator (such as its variance) by measuring those properties when sampling from an approximating distribution).

3. Results and discussion

3.1. Route assessment

3.1.1. Forum bath description

Cumae hosted the Forum bath and the smaller Republican Roman bath, known as the Central Roman bath or, improperly, named the "Tomb of the Sibyl" [16]. A topographical survey of the Forum bath is shown in Fig. 2. Its construction dated back to a time of intense building activity, which occurred in *Cumae* some decades after the construction of *via Domitiana* (95 AD). At that time, the Central Roman bath was already present in the city centre. The construction of the Forum bath suggested that the population increased as well as the visitors for commercial purposes mainly due to the presence of the port area linked to *via Domitiana*, allowing a fast connection to Rome, without the need to reach *via Appia* [21].

The Forum bath, which remains are shown in Fig. 3a, was located in the lower part of the city. It faced west, most likely to take the advantage of a better insolation at all hours [16]. The two public entrances are shown in Fig. 2:

- the east entrance was located nearby the intersection with the road towards the Forum, along the northern side of the *Capitolium*;
- the vestibule entrance lead to the *frigidarium* passing through a scenic colonnade (Fig. 3b).

The *frigidarium* was characterised by the presence of cold pools. Large windows allowed natural lighting. On the right and left sides of the vestibule, two public spaces were present serving as dressing rooms and for additional activities such as massages and anointing before entering the bath. Southward, a small room served as a corridor preventing heat loss as well as hot rooms. The pools for immersion showed in Fig. 4 were on the north, south and west sides of these rooms.

The bath contained five pools:

- two pools in the *frigidarium* labelled D_1 (31 m^2, water depth 1.4 m, volume 43.4 m^3) and D_2 (21 m^2, water depth 1.4 m, volume 29.4 m^3) accessible through a short staircase (Fig. 4);

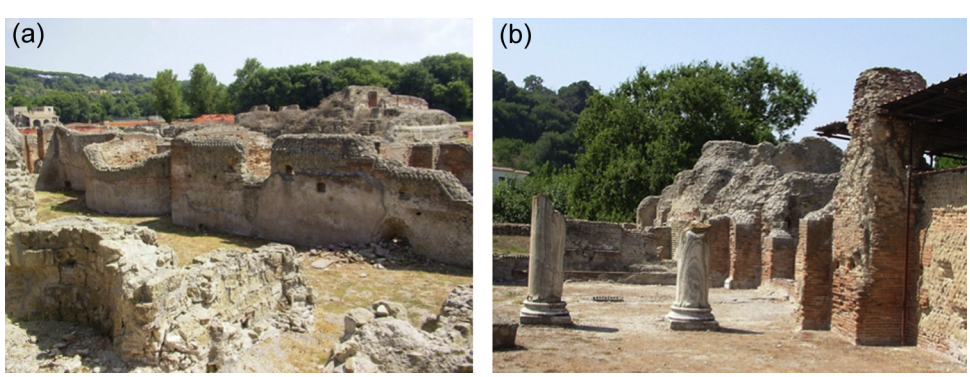

Fig. 3. (a) Remains of forum bath; (b) east entrance of bath and *frigidarium*.

Pictures taken by the authors.

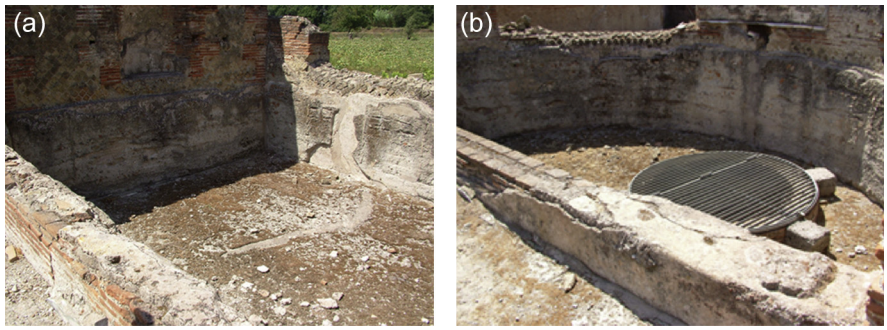

Fig. 4. Pools belonging to the *frigidarium* – D1 and D2 from Fig. 1.

Pictures taken by the authors.

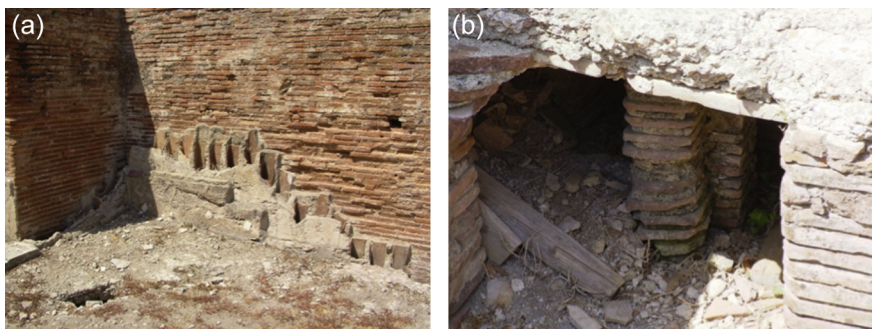

Fig. 5. (a) *Tubuli*; (b) *Suspensurae*.

Pictures taken by the authors.

- three inside the *calidarium* identified I_3 (12.5 m^2, water depth 1.4 m, volume 17.5 m^3), I_4 (14.5 m^2, water depth 1.4 m, volume 20.3 m^3), I_5 (13.5 m^2, water depth 1.4 m, volume 18.9 m^3).

The order of the rooms followed the usual sequence of Roman baths: *tepidarium* (medium temperature, Fig. 2 [F]), *sudatio* (for dry heat bath, Fig. 1 [G]), and *calidarium* (high temperature, Fig. 2 [H]). The heat produced by wood combustion was conveyed from the *praefurnium* (Fig. 2 [L]) throughout the above-mentioned series of rooms thanks to the *tubuli*, which was a system of cavities along the walls made of terracotta or brick pipes (Fig. 5a). The decking, lower than that of the adjacent rooms, was at the same level of the praefurnium, with some openings at the same level called the suspensurae, which were part of the floor heating system (Fig. 5b). They were coated with a 15 cm thick layer of waterproof plaster made of lime mortar mixed with sand or pozzolana and shards of brick [16].

A cistern, placed on a pedestal in the northwest corner of the bath, supplied water. The pedestal was located about 2 m over the base of the pools to facilitate the distribution of water. The cistern, originally divided into four tanks, was orientated in a way slightly different from that of the main complex. From the ruins' investigation, the cistern was 15 m long, 13 m width and 4.5 m depth (Fig. 6). Its perimeter wall had a thickness greater than that of the rest of the Roman bath (minimum thickness of 1 m), while the partition walls between tanks were thinner. The walls were primarily composed of opus reticulatum, interrupted at half height by eight rows of opus latericium (Fig. 6), covered with a thick layer of over 15 cm thick impermeable plaster. The plaster formed the pier caps at the corners between the wall and the floor, according to a technical solution common to both the ancient cisterns and modern tanks.

The cistern of the bath in the Forum operated as a *castellum aquae*, since it was positioned about 2 m higher than the bottom of the pools. The net area of the cistern was about 150 m^2; assuming an interior water level of 3.50 m, it could have contained about 525 m^3 of water. The assumption of considering an interior water depth of 3.5 m from the total height of the cistern (4.5 m) was adopted on the base of estimated literature values [25]. The total area and volume of the pools were 92.5 m^2 and 129.5 m^3, respectively. Therefore, the cistern volume was about four times greater than the amount of water necessary to fill the pools.

3.1.2. Rainfall data analysis

Results from the rainfall inference analysis suggested that:

- generally, a rainy year followed a drier one;
- annual values fluctuated in a periodic way with an average of 825 mm of rainfall (Fig. 7).

Fig. 6. Cistern feeding the pools.

Pictures taken by the authors (N in Fig. 1).

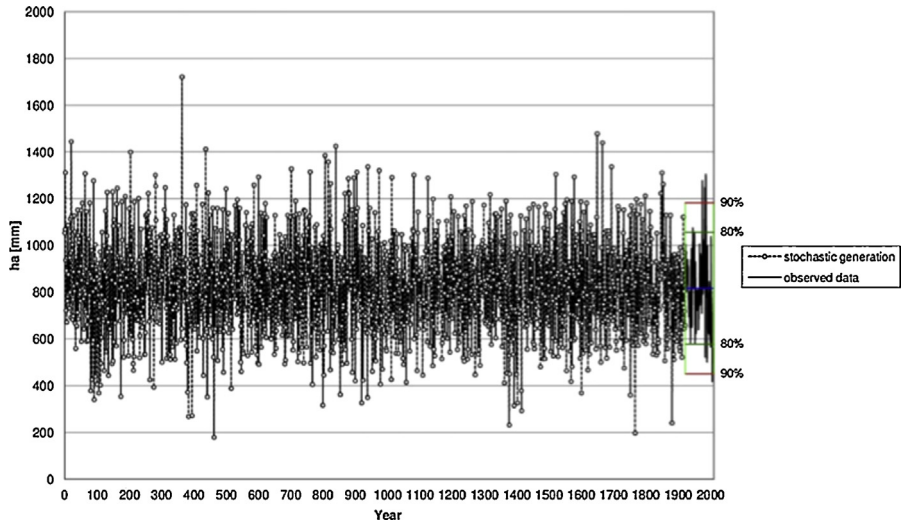

Fig. 7. Cumulative annual rainfalls in *Cumae* region; 0-1916 generated with a statistical analysis, in the last period (1916–2006), the confidence levels of 80 and 90% are reported with the observed data [24].

Considering the hypothesis of rainwater use and taking into account an average annual rainfall of 825 mm, the total average water volume that could have been potentially accumulated per year in the cistern was:

$$V = S_c \bullet h_m = 150 \bullet 0.825 = 123.75 \quad m^3 \tag{1}$$

where S_c is the net area of the cistern and h_m the averge of rainfall. The maximum water volume was 207.48 m^3 (with an increase of about 67%!) considering the rainiest year.

Thus, these volumes were insufficient even to fill the pools once per year. The statistical hydrological analysis of rainfall data over around 2000 years (Fig. 8) showed the reconstructed data between 0 and 1916 with a forecast confidence level of 80% and 90% (Fig. 6) harvesting rainfall data within 1916–2006 (Fig. 8). The maximum forecasted value of the cumulative annual precipitation was approximately 1,800 mm; therefore, no more than one tank of 270 m^3/year could have been filled. Although roof run-off could be conveyed to the tank, its contribution was negligible compared to the total volume.

As a consequence, the rainfall analysis confuted the hypothesis of the exclusive use of rainwater, suggesting that the Augustan Aqueduct supplied *Cumae*.

3.2. Flow assessment

The number of *Cumae* inhabitants during the first and second centuries AD is unknown to historians or archaeologists. The available records did not provide accurate data for the historical reference period and most of the town were not excavated. Thus, a calculation of the daily flow based on the available water supply per capita and the number of inhabitants is not possible.

Data derived from the characteristics of Roman bath and the volume of cisterns was used to determine both baths' water consumption and the potential daily number of visitors [30]. From these values, a rough estimation of the number of people present in *Cumae* and the flow delivered from the aqueduct to the city resulted feasible.

Assuming that the baths were open until sunset, a daily functioning of 12 h is plausible. The total submersion time of each

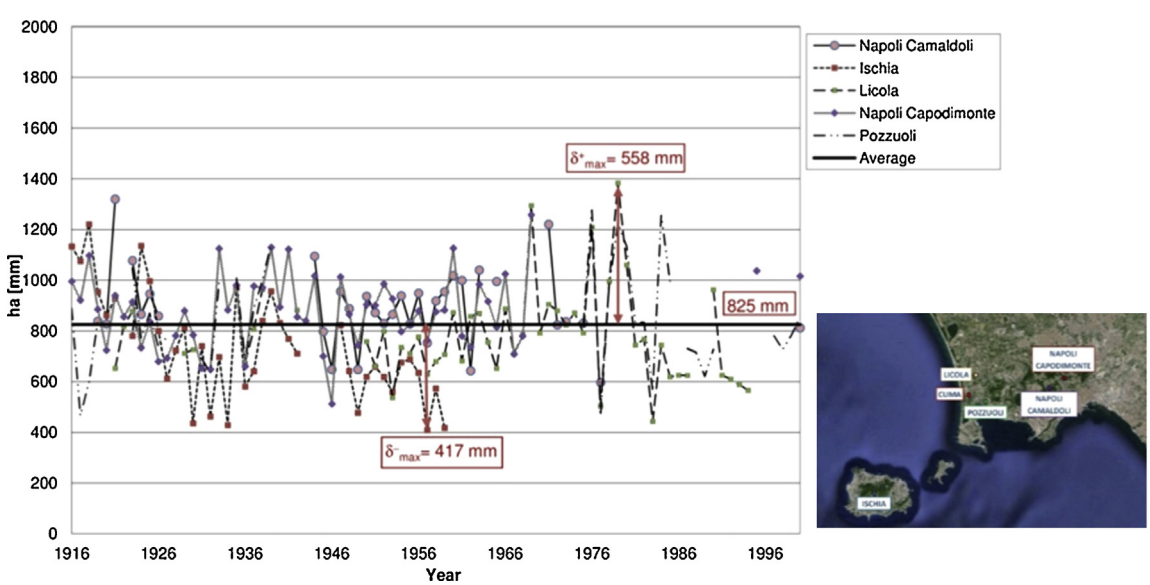

Fig. 8. Cumulative yearly rainfalls in *Cumae* region between 1916–2006.

person into the pools is estimated to be an hour (*frigidarium* and *calidarium*). If each person occupied an average surface area of 0.36 m^2 (assuming a square with sides of 0.60 m), increasing the value of 30%, each person could occupy a minimum area of 0.47 m^2 inside the pools. Since the total area of the pools is 92.5 m^2, a maximum of 198 people could be simultaneously present.

Assuming that 160 l (0.16 m^3) of water were used per day for personal care, the necessary exchange of water every hour, corresponding to 31.62 m^3, was obtained by multiplying the water volume necessary for each person/bath (160 l/d) by the number of users that could have been simultaneously present in the pools of the *Forum* of *Cumae*. Multiplying the number of people present at the same time within 12 h of bath operation, the total number of users was equal to 2372. The daily water flow necessary for the Roman bath function, inferred from these values, corresponded to 379.49 m^3/d, i.e. 4.39 l/s. The cistern of the *Forum* bath, therefore, with a volume of 525 m^3 of water, was sufficient to supply water for about 1 day. Based on the aforementioned data, *Cumae* could host more than 2000 inhabitants. The baths could attend a maximum of 2372 users per day, which was partly composed of the visitors participating in city trade.

The per capita water supply was evaluated considering two reference values:

- the value of *quinaria*;
- the per capita water supply of *Pompeii* [11].

According to Di Fenizio [26] and Rodgers [27], a *quinaria* corresponded to a flow rate of 0.48 l/s. *Pompeii* had about 12,000 inhabitants and the daily flow rate (calculated according to the new conduits) was equal to 6460 m^3/d. The per capita water supply of *Pompeii* corresponding to 0.54 m^3/d per person was obtained by dividing the daily flow rate by the number of inhabitants [25].

The difference between the two values is undoubtedly due to the fact that the *quinaria* takes into account only the personal consumption of water whereas the value for the city of *Pompeii* was calculated as the ratio between the overall scopes and the number of inhabitants – including the water used for domestic purposes, for public purposes and for decorative ponds and fountains.

It has been estimated that 10,000 sailors and 10,000 civilians constituted the population of *Misenum*. These 20,000 people would have had the same per capita water supply calculated for *Pompeii*, i.e. 0.54 m^3/d per person. The daily flow should have been 10,767 m^3/d, i.e. 125 l/s. This flow of water would have required more than a day to replenish the *Piscina Mirabilis*.

Another known datum is that the total population of *Nola, Acerra, Atella, Naples, Pozzuoli, Cumae, Baia* and *Misenum*, in the first century AD, exceeded 200,000 people [22], excluding *Pompeii* and *Herculaneum*, which, at the time, had respectively 12,000 and 5000 inhabitants [28].

The total population served by Serino Aqueduct would have thus met or exceeded 217,000 people. Although the other cities were not all similar to *Pompeii*, our study considered that the per capita water supply was of about 0.54 m^3/(d per person).

An identical per capita water supply was provided via the Augustan Aqueduct by a total flow rate of 1352 l/s. The current discharge of "*Acquaro-Pelosi*" source is 900 l/s [29]. The two values are well-matching since the source has been in use for over 2000 years.

Assuming that during the first and second centuries AD, the ancient city of *Cumae* had more than 2000 inhabitants with a per capita water supply corresponding to 0.54 m^3/d, the water flow of the branch aqueduct directed to *Cumae* from the main stretch of the Serino aqueduct could be estimated at 1076.7 m^3/d.

4. Conclusions

A hydrological analysis was carried out in order to exactly assess route, flow and uses of the water conveyed by the *Aqua Augusta* through the city of *Cumae*.

According to this analysis, the historical records regarding a branch of the Augustan Aqueduct, which would have reached the city of Cumae, were confirmed. The water flow of the branch aqueduct directed to *Cumae* from the main stretch of the Serino aqueduct was estimated corresponding to 12 l/s.

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