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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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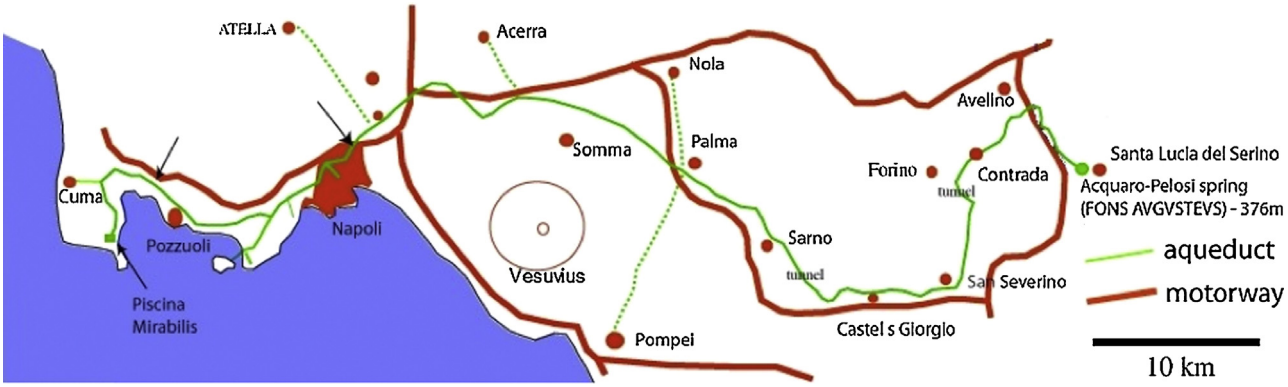

Fig. 1. Location of Cumae along the route of the Augustan aqueduct from Serino to Miseno.
Adopted from De Feo et al. [31].

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;