Water Supply from the Piscina Mirabilis to Roman Misenum

Investigation into the function of the Piscina Mirabilis and the supply of water to the Roman naval port of Misenum

Key words: *Misenum, Piscina Mirabilis, water supply, castellum divisorium, hydraulic engines, Augusta Aqueduct, Serino Aqueduct*

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1 Abstract

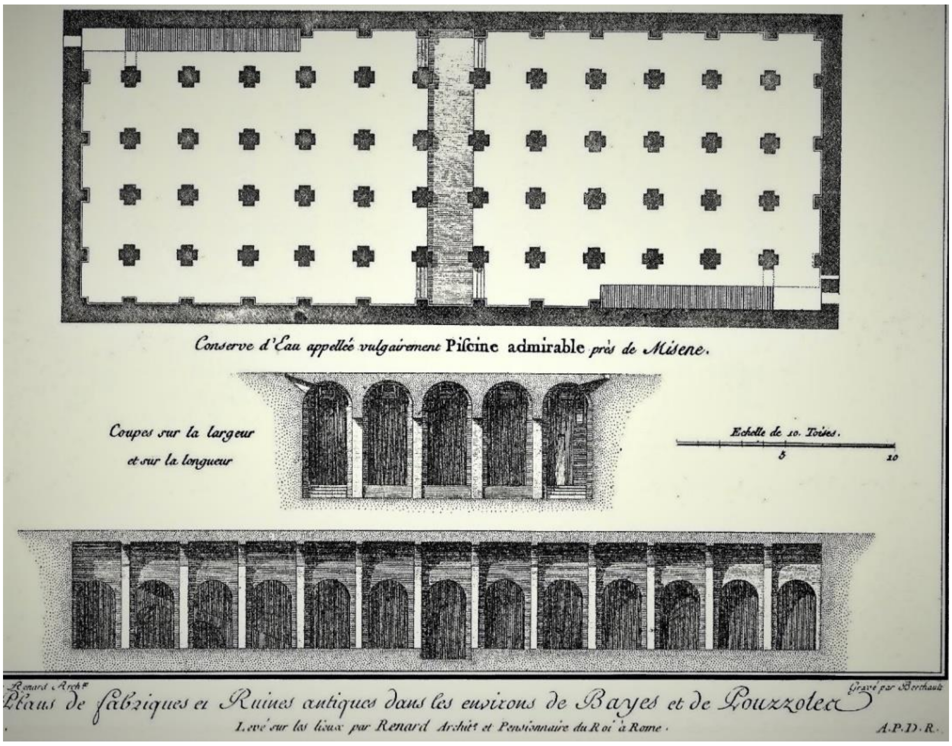

Figure 1 The Piscina Mirabilis - an engraving (Saint-Non 1782)

The Augusta Aqueduct (also known as the Serino Aqueduct[1]) was built, under the direction of the Roman Emperor Augustus, towards the end of the 1st Century BCE in order to provide fresh water to the naval port of Misenum (modern Miseno[2]), the headquarters of the Western Roman fleet. The Augusta is historically assumed to have terminated at the Piscina Mirabilis (Latin spelling, Piscina Mirabile in modern Italian), a large cistern built on a hill overlooking Misenum. Current documentation on the Piscina proposes that water was then extracted from the top of the Piscina for distribution to the town and dockyards of Misenum.

This paper discusses the reasons for the Piscina and its siting, and proposes that the Aqueduct flows would have continued past or through the Piscina into Misenum. A case is also made for the extraction of water from the Piscina at times when the flow of water from the Augusta was interrupted. A possible water distribution network to the old town of Misenum and the dockyards around the Inner and Outer Harbours of Misenum is also postulated.

2 Introduction

Roman engineers and project managers have had very little visibility. Ancient librarians concentrated on works of philosophy, politics and religion and it is these that were preserved and copied in medieval monasteries to be passed down to us. With a few notable exceptions[3], little is known of Roman engineers, of the builders of aqueducts, cisterns and piscinae, and next to nothing of the mid-level managers, surveyors and builders. Despite this lack of information,

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[1] The Augusta Aqueduct is also referred to as the Serino Aqueduct after its source springs. Previously the aqueduct was known as the Claudius Aqueduct due to an earlier belief that it had been built in the reign of the Emperor Claudius. The name Augusta has been used throughout this paper.

[2] Roman town names have been used throughout this paper. Lakes, gulfs and capes retain the modern Italian spelling as there is no consensus on the old Roman names for these.

[3] The two main exceptions are "De Architectura", or The Ten Books of Architecture written by Marcus Vitruvius Pollio about 27 BCE, and "De aquaeductu" on the maintenance, use of and distribution from the aqueducts of Rome written by Sextus Julius Frontinus circa end of 1st Century CE.

existing remains demonstrate construction and hydraulic skills which would not be matched for 1,700 years.

This paper is the result of the studies of John Allen and David Millar who have brought their professional skills, mechanical and hydraulic engineering, project engineering and operational analysis, plus their combined interest in Roman engineering, to this study of the Piscina Mirabilis, its inputs and outputs, and the provision of water to the Roman port of Misenum. Observations are recorded and hypotheses put forward relying on the groundwork of this study or extrapolated from the findings of previous researchers, many of whom have provided valuable assistance.

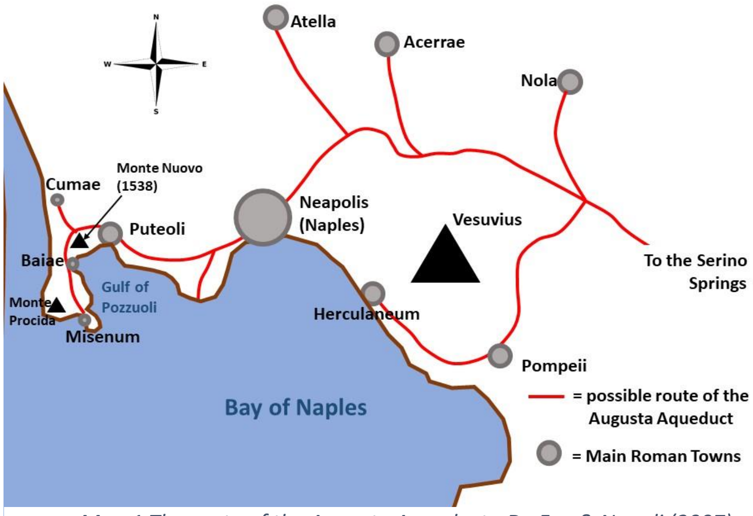
This research has referenced available literature on Roman techniques and history, but has been based, as far as possible, on personal observation and measurements[4], supported by the authors' personal and practical experiences as engineers and project managers. Measurements (dimensions and altitude) were taken outside and within the Piscina, and from the Piscina into the old town of Misenum.

A long section 4, on the structure of Misenum and its surroundings and on the operations of the Roman fleet, has the purpose of establishing the numbers and location of the population in Roman times and the consequent demands on the Piscina. This section is derived from the research of others and no new research or investigations took place.

Membership of the Cocceius Association (Associazione Cocceius) has proven highly beneficial. This is a non-profit association dedicated to exploration, study and research of ancient underground artefacts, in particular of the Campi Flegrei, Campania region. It is named after Lucius Cocceius Auctus, the architect and engineer responsible for much, if not all, of the design and construction of this Augusta Aqueduct and, possibly, the associated Piscina Mirabilis.

The conclusions may differ from those of previous researchers and the authors apologise for any perceived criticisms and welcome the opportunity to discuss these differences.

3 Background



Map 1 The route of the Augusta Aqueduct - De Feo & Napoli (2007), Keenan-Jones (2010), Ferrari & Lamagna (2015)

The building of the Augusta Aqueduct probably commenced shortly after the coming to power of Octavian, later to be the Emperor Augustus. Planning may have started as early as 27 BCE and the Aqueduct is believed to have been completed by 12 BCE[5] (Keenan-Jones 2010). It was built to service the Roman fleet, originally based at Portus Julius in Baiae but later moved to Misenum. The Aqueduct ran from the springs of Serino near Avellino (see Map 1) in the mountains northeast of

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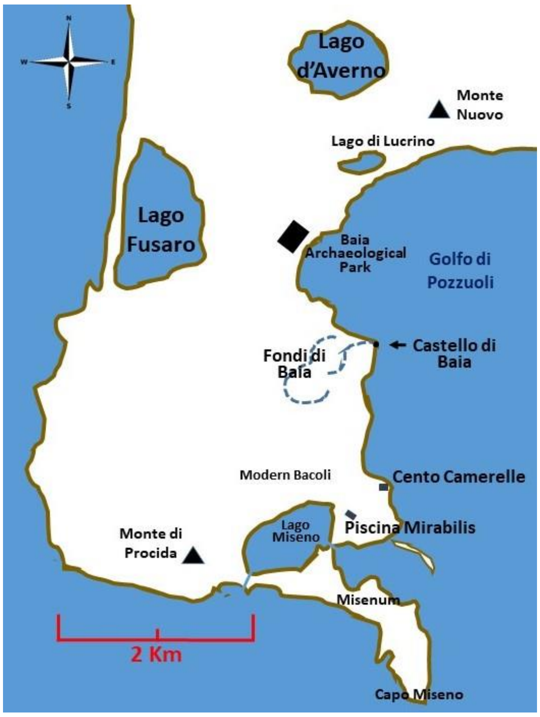
[4] Altitude measurements were taken using the Apple iPhone Altimeter Plus app. These have a high degree of inaccuracy and will never be as accurate as correctly surveyed methods. Wherever possible, the measurements are referred back to a base measurement taken at the same spot and within an hour of each other. In this way it is proposed that, whilst the absolute measurements themselves may have a high level of inaccuracy, the comparisons between them will be accurate enough for any findings.

[5] A stone engraving was found (Sgobbo 1938) that describes the Aqueduct and confirms the towns, including Misenum, that it served. Another commemorating the December 30th 10 CE inauguration of a new

Vesuvius, via Neapolis and Puteoli (Roman Naples and Pozzuoli), and on, to the Piscina Mirabilis in Bauli (modern Bacoli) on a hill opposite the port of Misenum, from where would have provided fresh water, bathing and sanitation to the town of Misenum, its naval dockyards and the fleet.



Map 2 Baiae, Misenum and the Peninsula

The port and the town of Misenum are situated on the peninsula which extends southwards from Baiae (see Map 2). The peninsula is approximately 3.5 km wide and 5 km from Baiae to the tip of Cape Miseno. It is predominately volcanic tufa or tuff (rock composed of fine volcanic ash particles fused together). There are few streams and, whilst the peninsula is not arid, there is not an overabundance of fresh water. There are three freshwater lakes near Baiae, Lago d'Averno and Lucrino (*Lacus Avernus* and *Lucrinus*) just north of Baiae, and Lago Fusaro (*Acherusia Palus*) west of Bauli but, with higher ground between them and Misenum, they would be unsuitable for providing an easily transportable supply of water. Also, as these lakes provided oysters and mussels in Roman times, it is possible that their water was brackish (sea water mixed in) and therefore not suitable for drinking or bathing.

There were many villas in the surrounding area and had been since around 150 BCE. These were the summer residences of wealthy Romans. Many of the remains of these are clustered along the shore to the east and northeast of the Piscina (D'Arms 1970). Roman villas were usually well equipped to collect rain water for domestic use but many would also have been serviced by the Augusta Aqueduct, either as a supplementary source or, later, as their prime source.

It is significant that the high ground running from Baiae to Misenum is probably the rim of an ancient volcanic crater, the basin of which is in the bay, the Golfo di Pozzuoli, between Puteoli and Misenum. The land level in the basin, both above and below the sea, has fluctuated by as much as 8 metres due to the phenomenon known as Bradyseism (the fluctuation of a part of the Earth's surface caused by the filling or emptying of underground volcanic magma chambers) which has resulted in many Roman villas, originally on the coast, now being beneath the sea (Milia & Giordano 2000[6]).

In geophysical terms, Bradyseism in the Golfo di Pozzuoli is a constantly changing phenomenon. Rapid changes have been experienced in the past hundred years and residents can testify to visible changes in their lifetime. During the study, residents on the high ground east of the Sant'Anna church in Bauli (see Map 3) spoke of the fact that areas of beach and residential premises, which they used to see looking northwards along the coast from their houses, are now under water.

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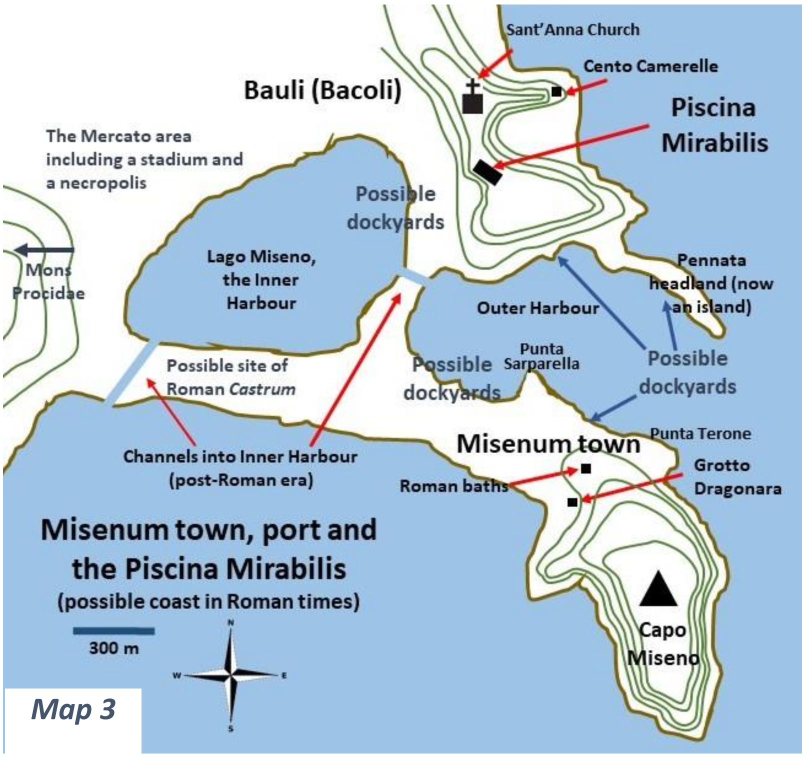
catchment area and tunnel servicing the Augusta was found in Scalandrone (Camodeca 1997 and Ferrari & Lamagna 2013), so the aqueduct was certainly operating normally by then.

[6] Morhange & Marriner, 2006 believe the rim is much further out and that the ridge on which the Aqueduct runs was actually inside the volcanic crater and would therefore have risen and fallen together with the seafront.

4 The Roman port of Misenum

4.1 The Port

The Roman naval fleet (*classis*) was created in the time of the Emperor Augustus (Saddington 2007). The fleet was split into two parts, the *Classis Misenensis* originally based at Portus Julius immediately north of Baiae, then at Misenum[7], and the *Classis Ravennatis* based at Ravenna on the eastern cost of the Italian peninsula.



Map 3

The port of Misenum consists of two parts, the Inner and the Outer Harbours, both probably the remains of ancient volcanic craters (see Map 3).

The **Outer Harbour**, open to the sea, is bounded by the Misenum promontory (on which stood the town of Misenum) to the south, and, to the north, the headland of Pennata (now an island following a storm in 1966 but previously connected to the mainland) and the promontory on which stands the Piscina Mirabilis. There is evidence of pillars and shipbuilding constructions on both sides of the Outer Harbour and the harbour was protected by breakwaters on the northern side (Illiano 2017). Underwater explorations have also shown a series of tunnels under the headland of Pennata connecting the Outer Harbour with the gulf of Pozzuoli. These may have been constructed to prevent any silting up of the harbour[8].

The Outer Harbour is connected, via a short canal on its northwest side, to the **Inner Harbour**, called Lago Miseno and also known as the Mare Morto (see Photograph 1). There is no evidence that the present canal is of Roman construction and, originally, the connection with the Inner Harbour may have been an open channel. This paper assumes that there was a water connection of some form to allow ships to pass between both harbours.

Lago Miseno, the Inner Harbour, is shallow and the sides are low-lying. This would have been where many of the Western Roman fleet would have been beached for the winter. The south eastern side of the Inner Harbour is believed to have contained docks and there is some evidence of constructions, possibly wharves, which can still be seen below the water level.

However this assumption has been questioned and an alternative suggested (Miniero 2008 and Iliano 2019). This is that the abovementioned Outer Harbour was actually divided by a mole or breakwater which projected from the Punta Sarparella north or northeast. This divided the Outer Harbour into an inner part and an outer part and that the outer part was protected from the sea by another mole between Punta Terone and the Pennata headland (see Map 3). Lake Miseno (the

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[7] Most documentation, i.e. McKay (1970), states that the move from Portus Julius was due to the silting up of the port entrance. D'Arms (1970) puts forward an alternative reason; that the Lucrinus and Fusaro lakes were famous for their oysters and that the fleet activity was ruining the oyster beds and, whilst this may have been ignored in time of war, during the peaceful times that followed, the rich and influential Roman gourmands may have influenced the move to Misenum.

[8] Illiano (2019) makes a case that these were in fact access tunnels to the docks which are now under water.

Inner Harbour or the Mare Morto) was then not an active harbour. This paper has not investigated either hypotheses as they do not affect the demand for water.

Photograph 1 The channel from the Outer to the Inner Harbour facing north

Photograph 2 The western channel from the sea to the Inner Harbour facing east

There is a second canal on the southwestern side of Lago Miseno which links the Inner Harbour to the sea (see Photograph 2). Again, there is no evidence that this existed in the Roman era, however, it is a short canal and well within Roman capability. It would have been a beneficial alternative entrance to the Inner Harbour.

The original old town of Misenum is that area on the part of the promontory south of the Outer Harbour stretching from the southern part of the Inner Harbour to the foot of the hill at the south end of the promontory. The larger urban area (*municipium*) of Roman Misenum should be considered to include, as well as the old town, the military camp area believed to be south of the Inner Harbour (the *Castrum*), the Mercato area west of the Inner Harbour, the town of Bauli to the east of the Inner Harbour, the area of dockyards and shipping facilities surrounding both harbours plus the hill above the Outer Harbour on which the Piscina is situated.

4.2 The Roman Navy

When considering the population of Misenum it is relevant to consider the Roman ships and their crews. A Roman military vessel was propelled by both oars and sails. But battles were fought using oars for propulsion with the objective of ramming an enemy ship and sinking or incapacitating it, or of locking onto the enemy ship, then allowing soldiers to board the enemy ship and fight hand to hand. Prior to a battle, the sails, many of the sailors and, possibly, the masts, would be left on shore so as to lighten the ships or to allow for extra soldiers to be taken on board. The crews of any ship therefore consisted of a number of distinct groups (Erdkamp 2007):

- the rowers, who supplied the propulsion during battle – mainly enlisted freemen but possibly, in times of stress, some conscripts, convicts or slaves;
- the professional sailors who managed the ship at times other than during battle;
- the shipborne soldiers (marines);
- the commander of the ship and his officers.

Ancient fleets did not cruise as a deterrent, but were usually in port other than when going into battle, supporting a military land campaign or chasing down enemy or pirate fleets. Also the fleet would have been at sea only during the summer sailing season as Romans rarely sailed in the stormy winter months. Ships would be hauled (*subducere*) onto beaches or into docks, often under cover (*navalia*) (Gardiner 2004; Morrison & Coates 1996).

4.3 The Population

Misenum was a thriving military town with the fleet, its officers, sailors and soldiers (marines or *miles*), as well as the many oarsmen required. There would also have been government and military officials, shipbuilders and workmen, ships suppliers, and all the supporting providers of medicine, food and entertainment, plus families and domestic slaves of many of the above. Misenum had also recently become an independent urban area, a patrician town with many high-ranking Romans (Illiano 2017, 2019). As well as the naval and ship building facilities it had, or had planned, temples, gardens, theatres and, relevant to this paper, public and private baths.

Between 27-18 BCE, based mainly on epigraphical evidence, it is believed there were 87[9] ships based in Misenum (Morrison & Coates 1996, Chapter 4, Appendix B), the majority *triremes* (warships with three rows of oars and one oarsman to each oar). Extrapolating (using Morrison & Coates estimates of crew sizes) these ship numbers gives a fleet of 12,000 oarsmen, 1,100 sailors and officers and 1,700 troops (estimates rounded), a total of just short of 15,000 men. On top of that there would have been families. Conservatively, assuming all oarsmen are single and that half the sailors and troops have a wife and one child, an extra 2,800 persons could have been resident in Misenum.

As well as the above there were administrators, shipwrights and naval craftsmen, shopkeepers and storemen, saloon-keepers and entertainers, plus the house slaves of the officers, administrators and many suppliers. A conservative figure for this group of non-naval supporters would be 3,000 – 5,000, giving a total of 20,800 - 22,800 persons (15,000 ship's crew, 2,800 dependants and 3,000 – 5,000 shore based residents) living in the greater Misenum urban area in the winter when the fleet was laid up in port.

These numbers are probably high given that they are based on the fleet size in the period after the Battle of Actium (or Aktion, in 31 BCE) and they would probably have reduced in the more peaceful times that followed. This number also would considerably reduce in the summer sailing season, when some or all of the fleet would be at sea, although the population of the villas of the wealthy would increase.

Furthermore it is likely that, during the winter, the oarsmen would not have been kept idle. Feeding them alone would have been expensive, and oarsmen would have had to be kept fit. The Romans were well aware of the need for training oarsmen and keeping them on suitable diets (Morrison & Coates 1996). It is possible then that some oarsmen were out of Misenum on various assignments. But this would also have been a time of training for the crews and it is probable that shore-based rowing rigs were used in addition to limited training in oared warships inside the harbours or nearby off-shore during periods of good weather.

The following assumptions were made:

- that in the summer, half the fleet (7,500) would have been busy elsewhere giving a population in all Misenum of 13,300;
- that in the winter 40% of the oarsmen (4,800) would have been out of town training or working at other locations, giving a population of 16,000.

Morrison & Coates (1986), in their description of Athenian crews, state that the skills required by oarsmen were sufficiently complex that they were specialists who would never be risked as supplementary soldiers. Extrapolating that, Roman oarsmen may not have been allowed to dissipate these skills in non-relevant labour, and it is therefore possible that the oarsmen were not released for other labour but were kept training all winter in or near Misenum and that this was an accepted expense. This would result in a larger military population in winter.

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[9] 15 Liburnians (light vessels with two banks of oars and one oarsman on each), 50 Triremes, 11 Quadriremes (a bank of 4 oarsmen on two or three oars), 1 Quincireme (5 oarsmen on three oars, 1 Sextareme (6 oarsmen on three oars) and 9 unspecified ships (Morrison & Coates 1996)

Regardless of winter and summer movements, there still would have been a short period during spring and autumn when the fleet was either fitting out for the summer campaign, or laying up in Inner Harbour after the summer, when a much larger number of sailors and oarsmen would have been in town. This could have been managed by gradually introducing sailors and oarsmen, but the population of the Misenum area could still have been 16,000-18,000 at peak periods, and food, accommodation and, pertinent to this paper, water would have to have been provided.

These numbers are key to estimating the water needs of the port and its surroundings, and the capacity needed of the Augusta. Apart from the general water needs of the population for drinking, bathing and sanitation, one must also take into account that water would be needed for taking on board ships prior to leaving port, for cleaning ships, and for the saw mills and forges building and repairing the ships.

These were the population numbers that would have been considered when the Augusta Aqueduct and its supporting infrastructure were commissioned.

The above population's water requirements may not have all been supplied from the Piscina. There is research (Illiano 2017, 2019) indicating that the military (oarsmen, soldiers and supporting tradesmen) were based in or near the C*astrum* to the south of Lago Miseno, the Inner Harbour, which had its own supporting social infrastructure, including a stadium, northwest of the *Castrum* in the area now known as the Mercato, and that there was a spur of the Aqueduct, for which traces were found, serving these that branched off before the water reached the Piscina.

Eliminating these seasonally variable numbers from the population, as well as the military families, supporting tradesmen and usual other trades also likely to have been located near the *Castrum* (supply and entertainment workers, etc) gives a population in "old Misenum", that is the promontory and the area immediately below the Piscina hill, of around 3,000-5,000 persons, with the rest located at the *Castrum* and the area west of the Inner Harbour of Misenum. This number for old Misenum town compares well against that estimated on the basis of known senior Romans of 3,400-4,000 (Illiano 2019). Assuming that water to the *Castrum* and Mercato areas was provided by an Augusta spur before it reached the Piscina, this is the number of persons, plus the dockyards, that would have had to have been provided with water directly from the Piscina.

5 The Augusta Aqueduct

5.1 Overview and History

The Augusta Aqueduct was built in the Augustan period (30 BCE to 14 CE[10]) under the direction of Marcus Vipsanius Agrippa (about 64 BCE to 12 BCE). Agrippa had been responsible for the fleet of Augustus (then known as Octavian or Octavianus Caesar) in his campaign against Sextus Pompeius, and then Marcus Antonius (Mark Antony) for supremacy of the Roman world, effectively culminating in the Battle of Actium in 31 BCE (Beard 2015).

Once Augustus was established as leader of the Rome world, Agrippa was established as a consul and was responsible for carrying out many major infrastructure projects both in Rome and in the Roman Empire. One of these was the construction of an aqueduct to solve the water requirements of a naval port in Misenum. This latter would have been of significance to Agrippa given his background of commanding all or part of the Octavian fleet at Actium and of being responsible for its assembly at the original naval base of *Portus Julius* in Baiae and for the training there of the oarsmen and marines (Morrison & Coates 1996).

Much, if not all, the design and construction of this aqueduct was entrusted by Agrippa to the Roman engineer, Lucius Cocceius Auctus. Cocceius was a freed slave, architect and contractor operating in the Naples area in the later years of the 1st Century BCE and the early years of the 1st Century CE. The Greek historian Strabo (63 or 64 BCE to 24 CE) attributes the *Crypta Neapolitana*

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[10] From Octavian's (Augustus) defeat of Antony and Cleopatra to the death of the Emperor Augustus.

(two parallel tunnels between Naples and Puteoli, one a road tunnel, the other carrying the Augusta Aqueduct), and the *Grotta di Cocceio*, which connected Lake Avernus and Cumae, to Cocceius. Cocceius appears to have been a major influence and participant in all the development works that went on in the late 1st century BCE turning the area into a major facility for the Roman fleet (Ulrich & Quenemoen 2013).

The Augusta Aqueduct runs from the hills northeast of Naples to the port of Misenum (see Map 1). The main channel is approximately 100 Km (62 miles) and along the route there were spurs to Pompeii, Nola, Acerra, Herculaneum, Atella and Cumae. It was in operation for 400 to 500 years (De Feo & Napoli 2007 and earlier authors). Although repeatedly renovated during the Imperial years it is probable that it fell into disrepair and disuse by the end of the 5th Century CE.

5.2 Aqueduct management

5.2.1 Water flows

> “*A Roman aqueduct could no more be shut off when not needed (except perhaps at its source) than can a river, not unless you provided somewhere else for the water to go.*”
> A Trevor Hodge, “Roman Aqueducts and Water Supply”, 2002.

In the Roman world, water was supplied continuously and it is rare that there were any major water storage facilities. The exceptions are the North African aqueducts with the huge cisterns for the North African colonies (Wilson 2001), the Piscina Mirabilis, for the Caracalla Baths in Rome, and the 5th Century CE cisterns of Constantinople. All other cisterns are relatively small, usually simply for the collection of rainwater and used by, at most, a few buildings.

Flowing water fed the baths, public water fountains, industry and those residences connected to the urban distribution system. Taps were a rarity, those that existed were not robust, and water was used as required with that unused serving to clean streets, flush out sewers, or running to waste into rivers or the sea. There was no point turning off a tap as one cannot turn off an aqueduct (Hodge 2002).

The water flow of the Augusta Aqueduct is estimated as being between 35,000 and 121,000 cubic metres per day at the source (Keenan-Jones 2010, with data from Blackman 1978; Hodge 2002; Chanson 2002) with the variation due to the climatic seasonal changes. Along the route spurs will have reduced this by diverting water to Pompeii, Nola, Acerra, Herculaneum, Atella and Cumae, and the cities of Neapolis (Naples) and Puteoli (Pozzuoli) would also have extracted much water.

The Romans managed their aqueducts, for repairs and maintenance, for preventing fraudulent extraction, but also to control the flow to areas in need (Frontinus). As the Augusta Aqueduct was built primarily for the provision of water to the western base of the Roman fleet at Misenum, it is logical that the Aqueduct flows all the way up to the source, would have been managed to ensure that sufficient water reached Misenum, and that extraction, by Neapolis and Puteoli for example, did not cause the flow to fall below required levels.

The water flow by the time the Aqueduct reached the baths complex in Baiae (now the site of the Baia Archeological Park, the Parco Archeologico delle Terme di Baia) has been estimated at 5,000 cubic metres/day (0.058 cumecs or cubic metres per second) and the height above the current sea level was measured as 32 metres. At this point the water channel is 0.4 m high and 0.4m wide with the water probably running at 0.3 metres deep (Ferrari & Lamagna 2015). This width is less than the upstream parts of the Aqueduct, usually 0.8 metres wide by 1.8 metres high (De Feo & Napoli 2007), and significantly less than some of the major aqueducts serving Rome. This would have been due to the lower water flows and it is assumed that this width continued on the remaining route to the Piscina. However, it is also worth pointing out that this size of channel could handle much greater volumes of water than the 5,000 m^3 a day. Using the Mannings Formula it is estimated that this channel could have handled 3 times this volume before overflowing[11].

But this still makes this a very low-volume aqueduct by Roman standards. For comparison the average amount of water delivered by the nine aqueducts supplying Rome is over one million m^3 per day with the Marcia alone delivering 187,600 m^3 a day (Hodge 2002). And any estimates need to take into account that calcium deposits (sinter, Frontinus refers to this as calx) would have narrowed the channel and increased the roughness of the surfaces, reducing the flow further. There is no information on how often these channels were cleaned and how effectively.

The baths complex at the Baia Archaeological Park, as well as any branch to the military camp (*Castrum*) would have further reduced the flow, as would have any siphoning off for the villas on the route, including the villa, attributed to Julius Caesar, on the site of the current *Castello di Baia*, on a headland just south of Baia (Miniero 2010). But as already stated, given the importance of Misenum as a military port, the flow of water would have been managed to ensure that the volumes were kept at a level sufficient to the needs of the port.

5.2.2 Water usage

This paper does not attempt to calculate the actual water requirements of urban Misenum. There are too many variables between the needs of Roman citizens, military, oarsmen, slaves, provisioning the ships, and the needs of the dockyards. Instead the amount of water available is calculated and then evaluated as whether sufficient for a Roman military town of this size.

As seen from the calculations above (Ferrari & Lamagna 2015) the Aqueduct delivered at the point it reached the baths at Baia, a maximum of 5,000 m^3 or 5 million litres of water, per day.

Along the way from the point of measurement, water from the Aqueduct would have been diverted into the following uses:

a) The baths at Baiae and the Julius Caesar Villa beneath the Castello di Baia. A conservative estimate would be that 10% of the flow was diverted to these,

b) Villas between the Belvedere di Baia, through Bacoli and up to the Church Sant'Anna. 5% would be an ample provision.

That leaves 85% of the water that flowed from above the Baia Archaeological Park to be spread between the *Castrum/*Mercato branch and the Piscina. The spur to the *Castrum* would be a major diversion with potentially two to three times as many personnel of the *classis misenensis*, their dependants and their suppliers as in the town of Misenum itself. An obvious option would be to divide this 2½:1 in favour of the *Castrum* given its greater population. But (i) the majority of the shipyards and their supporting workshops and warehouses were in the areas fed by the Piscina (see Map 3), (ii) the Piscina would have fed the baths, civic buildings and fountains of Misenum old town, (iii) the military would have used and been granted less water per person than the patricians of Misenum old town, and, finally, (iv) the slopes of *Mons Procidae* (Monte di Procida) would have provided rain water and springs which provided extra water resource to the *Castrum* (Illiano 2019). 35% of the water flow is therefore allocated to the *Castrum* branch, leaving 50% of the waters, 2.5 million litres per day, to reach the Piscina.

All the above calculations are hypothetical, but by breaking down the water usage one is more likely to approach reality. On this basis the 2.5 million litres of water available per day to a permanent population of 3,000 to 5,000 would allow 500 to over 800 litres per person per day. This is comparable to 500 litres per day in Rome at its peak (Hodge 2002) and can be considered ample for the people, the baths, fountains, the shipyards and the provisioning of ships, and would

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[11] Based on the same channel dimensions, the Mannings Formula Channel Flow Calculator at http://clem.sturmfels.com.au/channel-flow/ which, assuming smooth concrete surfaces (n, the roughness coefficient = 0.012, taken from https://www.eng.auburn.edu/~xzf0001/Handbook/Channels.html), gives a theoretical maximum flow velocity of 1.25-1.50 metres per second (as opposed to the Ferrari & Lamagna estimate of 0.5 m/sec). The Ferrari & Lamagna estimates, being lower, have been used in this paper.

leave a surplus in case extra water was needed by the *Castrum* and its surrounding area. As was the usual Roman practice, the excess water would be used to clean streets and market places, and to flush out drains and sewage systems.

6 The Piscina Mirabilis

6.1 Overview

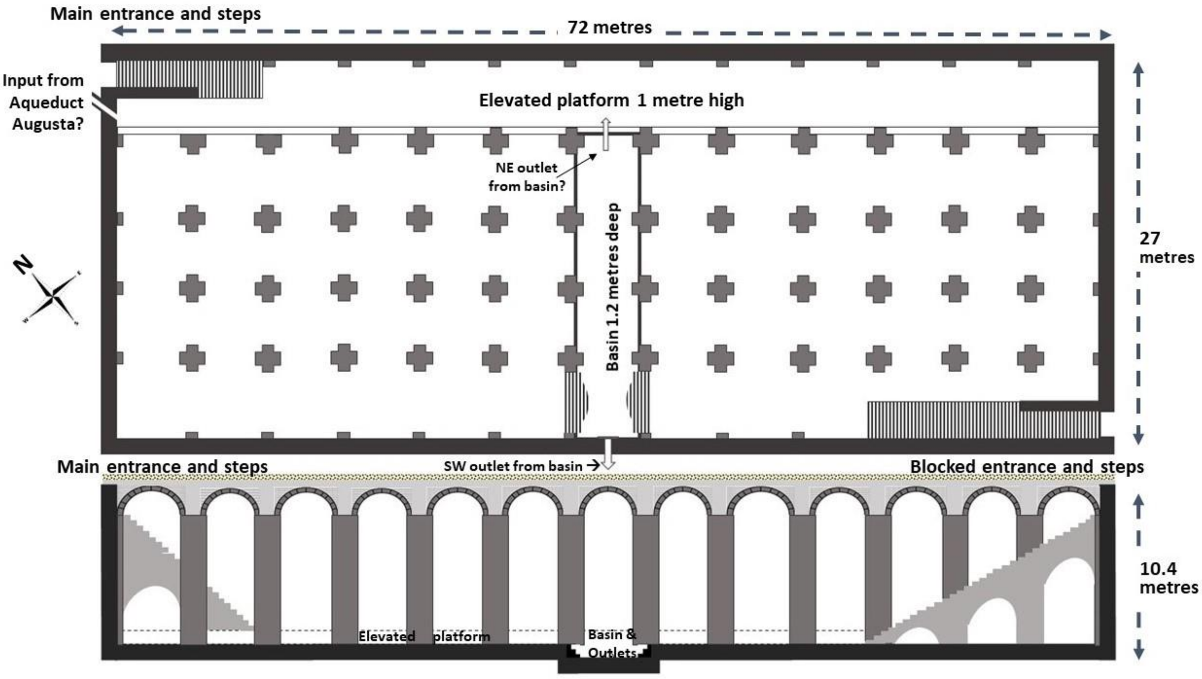

Figure 2 The plan of the Piscina Mirabilis

The Piscina Mirabilis is a large building, of Roman construction, on a hill overlooking both the Inner and Outer Harbours of the port of Misenum. It is partially embedded in the volcanic tuff rock. As a part of the Augusta Aqueduct system it can be considered to have been built in the period 30 to 10 BCE.

The Piscina is in remarkably good state given it is over 2,000 year old. It is likely that after the Aqueduct ceased to flow in the late 5th Century CE or earlier, the Piscina was used for storage, animal or vegetable, and gradually accumulated a lot of debris. However, much of the full magnitude of the Piscina was still visible over one thousand years later, as can be seen in 17th and 18th Century engravings, for example on page 86 of "Ager Putoleanus" (Villamena 1620) and on plate 61 of "Antichita Di Pozzuoli" (Paoli et al. 1768) as well as that from "*Voyages Pittoresques de l'Italie*" (Saint-Non 1782) shown at the front of this paper (Figure 1).

In the period 1910 to 1936 this debris was dug out and restoration work carried out including the application of waterproof cement (Rispoli et al. 2015). Care must therefore be taken in drawing conclusions based on cement applied by the original Roman builders (*opus caementicium,* a blend of lime, powdered volcanic tuff and sea water, also referred to as *pozzolan* or *pozzolana*) and the cement, which may have been made to a similar composition, used by the restorers in 1910-36. Since these works, restorations have been limited to placing a modern protective metal access staircase above the restored access staircase on the NW corner plus installing weather protection on the outside of the roof.

6.2 Reasons for a Piscina

The first question to be asked is "why is the Piscina Mirabilis position where it is?" Indeed "why is there a piscina, a water cistern there at all?"

Photograph 3 Visitor entrance at the NW corner with entrance to Piscina in the background

Photograph 4 Longitudinal view of an internal aisle

If there was simply a need for a flow of fresh water to Misenum it would have been simpler and cheaper to continue the Aqueduct south following a steady downward path to bring it to the edge of the Inner Harbour close to sea level. Water could simply flow into an open channel on the north side of the Inner Harbour which could then circumnavigate the Inner Harbour on its east side and then continue towards the old town on the peninsula. It might need a low single arch viaduct or earth embankment to keep the water level at a height sufficient to reach the baths in the old town, but this would be a relatively simple and cheap construction. By this means no cistern/piscina is needed.

Is it possible that the Piscina could have achieved its purpose by collecting only rainwater? The Piscina is near the top of the hill on which it stands. There is little higher ground suitable for collecting rainwater. The annual rainfall in Roman times is not known but the current average annual rainfall in Naples is 100.6 cm, just over a metre. This is insufficient to maintain water levels in the Piscina simply using the rain that fell on or near it.

Why then did the Roman engineers go to the effort and expense of building a massive cistern and the viaducts necessary to reach it? There are two obvious logical reasons:

a. To provide a store of water in an emergency when the Aqueduct supply was cut off, and
b. To provide water at a sufficient water pressure or momentum/velocity (i.e. kinetic energy) to more effectively manage the supply to the port, the naval dockyards and the town.

The original reason may have been to provide the back-up supply of water. Misenum was a naval base and could not be allowed to cease functioning effectively, and, with only one aqueduct supplying Misenum, unlike cities like Rome and Lyon which had multiple aqueducts, any disruption, whether accidental or for maintenance, would have been a serious problem for the Misenum shipyards. Misenum needed a back-up supply of water that enabled it to continue operating without deterioration of the service for the maximum possible number of days.

This requirement was satisfied by providing the cistern. The Piscina, held nearly 14,500 m^3 (14.5 million litres) of water which, based on an average population of 4,000 persons and a supply of 500 litres per person per day, was enough water for 5.8 days. This would be sufficient that, in the case of a temporary closure of the Aqueduct for maintenance, there would be no impact on the working of the naval base.

Option (a) above could still have been satisfied by building a cistern on the level ground on the east side of the Inner Harbour on the route described above, perhaps on top of an earth mound close to sea level. Such a facility could easily have been built to a much larger capacity than the Piscina Mirabilis. Effectively the Romans could have built an artificial freshwater lake.

Photograph 5 Satellite view of the Piscina Mirabilis (Google Earth Pro)[12]

The only logical reason for building a water storage facility at the top of a hill, as well as the significant expense of building a major elevated viaduct to reach it, is to store the potential energy of the water, i.e. the energy due to the height of the water, and to create a storage facility which retained that energy and allowed water to be channelled through pipes with an amount of pressure, i.e. kinetic energy.

As already noted, the flow of water into the Piscina from the Augusta is relatively low – 2,500 to 3,000 m^3 per day (29 - 35 litres per second) compared to that of other aqueducts channelling up to 60 times that volume. Low volumes of water on a level or very slightly inclined plane are difficult to handle satisfactorily. Even Roman taps, estimated at capable of handling the pressure of only up to 6-6.5 metres in height (Lorenz 2013), would need some minimal pressure to work satisfactorily.

Water pressure would have made it easier to force water along the flat land to the old town of Misenum, would have enabled better public fountains and improved the facilities for the ship builders and repairers. But to benefit from this water pressure required the existence of enclosed water pipes on sections of the water supply following the Piscina. Pressure would clean pipes, allow fountains to present a jet of water, enable hoses and water jets in industry, and provide a more satisfying environment in the public baths. The natural flow in an open channel from the Augusta is insufficient to satisfactorily provide these benefits. Water falling from a height but in an open channel, for example as in a waterfall, provides immediate power and could be used to turn a water wheel, but that energy is rapidly dissipated once the water hits the bottom of the channel. To provide both continued energy and control requires both a height of water to create pressure, and enclosed pipes to retain that pressure. Whilst the Romans may not have understood the mathematics behind this principle, their engineers would have had good experience of the benefits and practicalities of creating such a system.

A question must be asked. Did the Romans plan for a storage cistern from the start and did they plan to build it at a height, so increasing water pressure? Building the Piscina Mirabilis and constructing a two to three arch high viaduct to feed it would have added considerably to the time

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[12] *Seen from the northeast. Note the roof openings, now covered with modern protection, as well as the massive buttresses supporting the Piscina walls on the NE side.*

taken in construction and the cost. Or was the need for the Piscina and its positioning at a height above Misenum decided at a later stage when it was realised that a single source of water was too prone to disruption and that the volumes of water provided were insufficient to effectively serve the town, military and dockyards?

One assumes that the designers of the overall water provision produced plans and cost estimates, possibly by Lucius Cocceius Auctus himself, and submitted these to Agrippa for approval. Sadly none of these documents have survived so the above questions will remain unanswered.

6.3 The function, size and volume of the Piscina

Photograph 6 Supporting buttresses on the external NE wall

The Piscina Mirabilis is dug into a hill overlooking the port of Misenum. It is embedded into Neapolitan Yellow Tuff, deposits of which were laid down by the Phlegrean Fields eruption about 15,000 years ago, with only the long NE side being unsupported. This NE side is, currently, partially embedded in the surrounded earth but also supported by massive external buttresses[13] of unmistakeably Roman construction (see Photograph 6). The spaces in between these supporting buttresses show signs of having been used for dwelling or retail purposes and they have been referred to as "shop bays". But this cannot have been their primary purpose. Shops are not built with dividing walls of such a thickness. These are undoubtedly supporting structures.

The Piscina is 10.4 metres high (from the floor to the roof), 27 metres wide and 72 metres long (both internal measurements – see Figure 2). The four rows each of 12 cruciform pillars down the length of the Piscina divide it into five naves and supporting barrel vaulted ceilings with the lengthwise arches being higher than the arches across the short width of the Piscina.

There is a row of holes of varying sizes running in a line along the centre of the roof. There are also holes irregularly positioned closer to the sides of the Piscina (Rispoli et al. 2015). It has not been

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[13] This paper refers to the central piers in the Piscina as "pillars" and, where these are attached to an internal or external side wall, as "buttresses".

possible to ascertain whether any of these holes are original or are later additions. Along the foot of the long northeast wall there is an elevated platform approximately 1 metre high and 5 metres wide. The purpose of this is not apparent (see Section 8.1.6). Note that this elevated platform is absent from the Saint-Non engraving of 1782 (see Figure 1). It is assumed this is an error on the part of the artist.

The walls of the Piscina are lined with tuff bricks in *opus reticulatum* style (square ended bricks laid at an angle to create a diagonal pattern), with a 6 layer line of kiln-fired brick tiles, 2.8 to 2.9 metres above the floor of the Piscina. This line of tiles (*opus latericium*) runs all around the inside of the Piscina including on the side buttresses, an indication that the walls and buttresses are original. The internal buttresses against the walls appear to be of kiln-fired bricks[14]. Both these and the tuff bricks forming the sides of the Piscina are covered with Roman waterproof cement (*opus caementicium*).

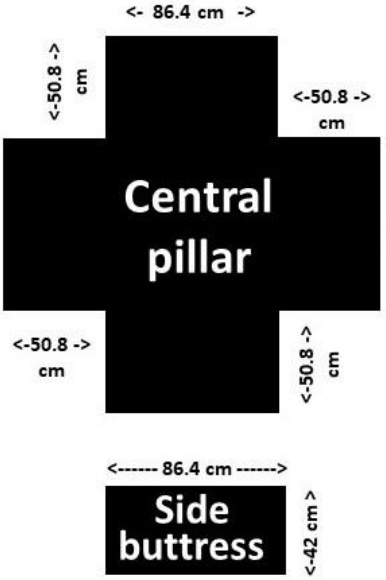

Figure 3 Central pillar and side buttress

The central pillars, in the shape of a Greek cross (see Figure 3), are of large tuff ashlars also covered with *opus caementicium*. The floor of the Piscina is also of this cement mixed with larger terracotta fragments, *opus signinum (*Roman cement, usually *opus caementicium* mixed with finely ground fired clay tiles or even pottery, also referred to as *cocciopesto*).

The Piscina is roofed, probably to prevent evaporation during the hot Campanian summers and to prevent plant or bird matter falling into the water. It is assumed the holes are to allow light for workmen, to enable inspection from above and to improve the circulation of air within the vault. This feature is seen in the piscinas of North Africa which operated under similar conditions (Wilson 2001) although these were built 150-250 years after the Piscina Mirabilis. They could possibly also be used for the extraction of water (see Section 6.6.1).

The street entrance level of the Piscina is 17 metres above the current sea level. It is estimated (Dvorak and Mastrolorenzo 1991) that the overall sea level of the Mediterranean in Roman times was 0.5 metres lower than today's levels. In addition local Bradyseism has lowered the land, the sea floor, by anything up to 8 metres in parts of the Gulf of Pozzuoli. Given the sight of the remains of the old, possibly Roman, docks underwater in the Inner Harbour, Lago Miseno, it is estimated that the abovementioned street entrance level of the Piscina was then 20-22 metres above Roman sea levels.

The Piscina is 10.4 metres from the roof to the floor (the drain space is 1 metre lower), but the high water mark, the maximum depth to which the Piscina could be filled was to the lower level of the input channel or to the entrance door, whichever was the lower. Water above this level would simply back up into the Aqueduct or flow out of the door. The probable input channel (see Section 6.5) is two metres below the roof. This is higher than the threshold (lower step) of the entrance door, so the maximum height to which the Piscina could be filled was to this threshold, 8.4 metres

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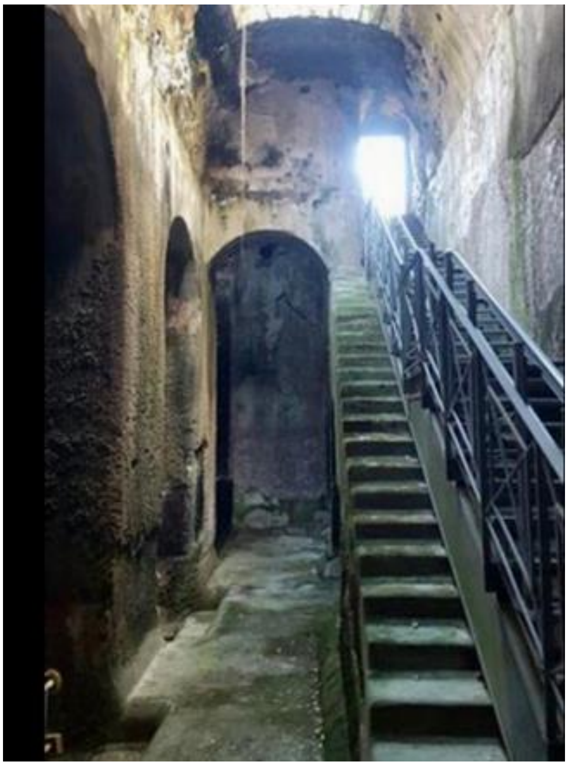
[14] The Theatre of Marcellus in Rome is believed to be the first Roman building built of fired bricks although fired bricks had been known to the Greeks for a few centuries at this time. It was completed in 13 BCE but construction is believed to have started in the time of Julius Caesar (died 44 BCE). Another example is the tomb of Caecilia Metella that was probably built in the beginning of the 20s BCE. The fired bricks in the Piscina would be another very early usage of fired bricks. It should also be noted that the Ponti Rossi viaduct on the Augusta Aqueduct upstream of Naples is also built of what appear to be kiln-fired bricks. This would have been built at the same time as the Piscina.

above the main floor. Assuming the lowest land level in Roman Misenum to be 1.5-2 metres above sea level, the water level in the Piscina was therefore between 10 and 19 metres above the town.

There is also a ditch or basin approximately 120 cm deep below the level of the main floor and 4.3 metres wide, halfway along the Piscina (see Photograph 13) with a large hole (now blocked up) at the south end and a smaller blocked hole at the other end. It has been assumed in the past that this was for the collection and drainage of sediment and waste, and the complete draining of the Piscina for repair work. If so there would have had a method of sealing this off but any trace of grooves for a sluice or trapdoor have been obliterated in what is a fairly crude later application of cement. The purpose of this basin is looked at in Sections 6.6.5 and 8.1.4.

Allowing for the volume taken up by the pillars and internal buttresses, the elevated platform on the long NE wall and the steps, the effective water-holding volume of the Piscina, including the central basin, is 14,469 m^3 (this figure is greater than the figure of 12,600 m^3 quoted in Hodge 2002; De Feo & Napoli 2007; De Feo et al. 2013). The Piscina holds 5.79 days' worth of Misenum's normal water usage.

It is possible that there was therefore a maintenance walkway within the Piscina around the walls at a height above the high water level. This occurs in some of the North African water cisterns (Wilson 2001). If so, it was probably of wood and no trace remains. Any supports in the side walls have also disappeared and there are no obvious post holes visible. There is a ledge at the top of the pillars and buttresses (see Photograph 8). This ledge could have been for the support of a walkway or it could have been used in the construction of the Piscina for the support of the wooden frames used in building the arches. It is also possible that there was no walkway and that maintenance was carried out by labourers operating through the holes in the roof.



Photograph 7 Front (main) entrance steps

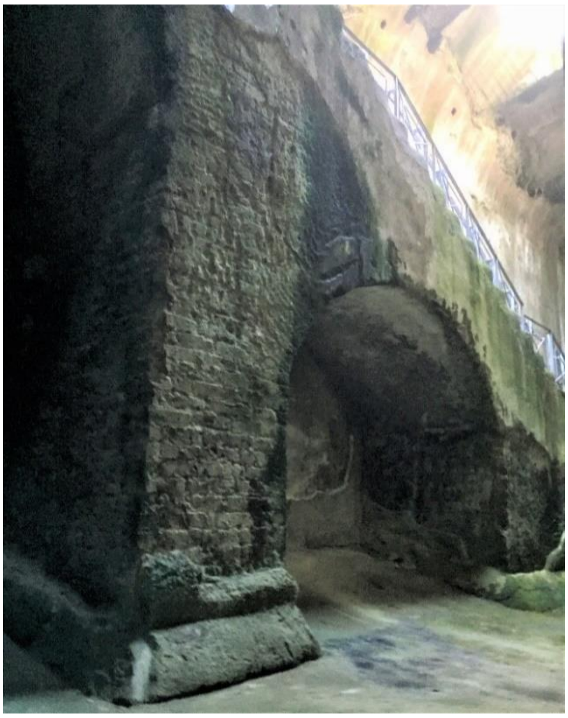
The modern protective staircase is to the left. The input of the Augusta Aqueduct to the Piscina is within the far arch to the right of the dark hole that can be seen.

Photograph 8 An internal aisle

The ledges, possibly for supporting wooden walkways, can be seen at the top of the pillars. Or are these supports for the wooden frames used in constructing the arch?

Photograph 9 The back entrance and steps

This entrance, diagonally across the Piscina from the main entrance, is currently sealed.



Photograph 10 Below the main entrance steps

Note the fired brick pillar and the, possibly Roman concrete, "pulvinus" or plinth at the base.

Photograph 11 SE side wall of the Piscina

At the top the 6-layer line of fired brick tiles are seen surrounded by opus reticulatum. Below the wall is coated with opus caementicium. At the foot is a layer of concrete approximately 35 cm high which runs round most of the Piscina walls.

Photograph 12 Wall between two side buttresses

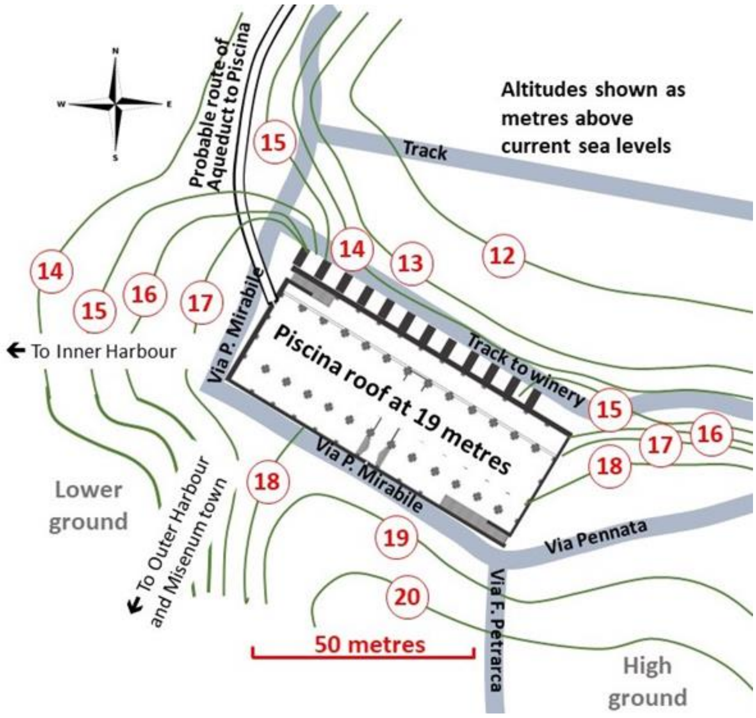
The 6-layer of brick tiles can be seen with opus reticulatum above and below it. The lower part of the wall is still covered with opus caementicum and the floor in the foreground is opus signinum.

Photograph 13 The central basin

Photograph 14 One of the ten roof opening from below.

Note the possible water exit at the far end, the top right hand of the photograph.

6.4 The position and elevation of the Piscina



Map 4 The Piscina showing the surrounding land and elevations

Map 4[15] shows the elevations in the immediate surroundings of the Piscina. This shows that the most efficient and economical route for the Aqueduct to the Piscina is along a ridge running south from the high ground now occupied by the Church Sant' Anna to the north corner of the Piscina. To run either to the east or west of this ridge would put it on land much lower than the top of the Piscina and would have required extensive extra viaduct work.

The Piscina Mirabilis is approximately 200 metres east of Lago Miseno (the Inner Harbour) and 300 metres north of the nearest edge of the Outer Harbour. This position of the Piscina makes it suitably positioned to provide water to:

a) The old dockyards on the north side of the Outer Harbour as well as those on the Isola di Pennata (an island now, but a promontory in Roman times). A route following the contours this would be a distance of approximately 1,300 metres.
b) The eastern side of the Inner Harbour - this would be a simple direct line downward pipe or open channel. The distance is 200 metres.
c) The Old Town of Misenum and its dockyard facilities on the southern side of the Outer Harbour. This would have required an inverted siphon or a viaduct as the land at the far end of

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[15] Altitudes were plotted using Google Earth Pro 7.3.4.8248. Note that these altitudes are those above the current sea level. Also that road levels commonly change over time and that the original Roman roads may have been one or two metres below current levels.

old Misenum town, particularly the Roman baths, is at a higher level (up to 8 metres above current sea levels) than the intermediate terrain. A long inverted siphon is the more likely solution as it would generate enough pressure to raise the water to the highest part of Misenum old town. No trace of any such viaduct or pipes has been found. The distance to the end of Misenum town is approximately 1,600 metres. It is conceivable that the branch of the water network then disgorged into the Grotta Dragonara, another cistern carved into the foot of the hill of Cape Miseno and used to collect spring and rain water from the hill at the end of the peninsula.

For further discussion on this, see section 7.

6.5 Input to the Piscina

At what point did the water from the Aqueduct enter the Piscina? As discussed above, this must have been close to the north corner of the Piscina, the junction of the long NE and short NW walls. Even so, the channel would have entered the Piscina at an angle and it is important that this angle is no less than 45 degrees to the Piscina. Given that the channels in Roman times were of stone or concrete, a lesser angle would cause the water input to erode the side of the Piscina wall.

Photograph 15 False or non-Roman cavities

The light area to the far left of this photograph is the sunlight from the overhead aperture.

There are traces of a number of holes in this area, all bricked up. To the left of the entrance doorway (in Photograph 15), on the NW wall and within the first row of arches from the long NE wall, is a small rectangular hole, too small to be an aqueduct entry and it would have to cut across the entrance doorway making access difficult. Note that what appears in this photograph to be two overlapping holes to the left of this is simple shadow due to a change in the cement.

There is a large bricked in area visible on the internal NE wall just above the steps. This is both too large and too low for an aqueduct entry and conflicts with the buttresses on the external NE wall. It may be early repair work.

Photograph 16 Probable Aqueduct entry on right - note arched top

At a level slightly above that of the entrance door threshold, on the short NW wall and within a supporting arch on that wall, is a large blocked up hole, 8.4 metres above the level of the main Piscina floor (see Photograph 16), and this is the best possible candidate for the entrance of water from the Aqueduct. This hole also displays evidence that the entry was at an angle of approximately 45 degrees to the wall, the angle that would have occurred with the Aqueduct coming in at near direct north and striking the NW facing wall of the Piscina. It also exhibits the expected shape, flat at the bottom and arched at the top, that one would expect of an aqueduct cross-section.

Alongside this are two larger round holes. These can be discounted, as an aqueduct channel is rectangular and to change to a circular channel would create unnecessary turbulence. These round holes probably come from a more recent era.

6.6 Extraction from the Piscina

6.6.1 The possible use of Hydraulic Engines

It has been suggested (Maiuri 1958) that, as no exit holes were observed, water was extracted from the Piscina by means of water wheels above the terrace and channelled from there towards the town and the port. This proposal, expanded to refer to hydraulic engines in general, is often repeated (De Feo et al. 2013) and on the visitor information board at the Piscina.

Extracting water through the roof would have lost the benefit of water pressure/kinetic energy, and would have required expending energy to lift the water, but, given its frequent mention, this has been investigated.

Firstly, what would be the quantity of water to be raised? The population would expect their daily 500 litres of water, so one must assume that that daily input to the Piscina would have to be raised. Any less and the Piscina would overflow. Whilst an overflow is always necessary, this should have been used only in emergencies as overflowing water would simply go to waste. This means that the weight of 2.5 million litres, 2.5 million kilograms or 2,500 metric tonnes would have to be raised in a single day.

Secondly, how high would this weight have to be raised? The height of the Piscina from the floor to the roof is 10.4 metres but the water was only 8.4 metres deep. If the Piscina was always full, then the water would have to be raised 2 metres, say 2.5 metres to allow a bucket or suction pipe to be immersed. But if, in times of water shortage, the Piscina was not full, the water would have needed to be raised up to 10.9 metres[16].

The main hydraulic engines available to the Romans were the Archimedes Screw, the water wheel, the bucket on a counter-weighted beam (the Egyptian "shaduf") and the "bucket and pulley". Small force pumps were also known to the Romans. Each option has been investigated.[17]

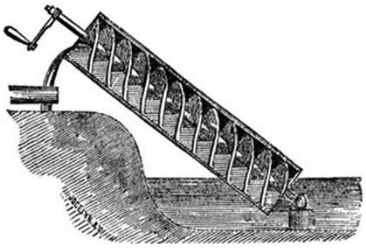

Figure 4 Ancient Archimedes Screw

A modern motor-driven ***Archimedes Screw*** can raise water to a maximum of 12 metres but a hand-cranked (or one driven by animal power) has a maximum lifting height of about 2 metres. Beyond this the weight of the water within the screw becomes too much for the screw to be turned. Wooden and iron Archimedes Screws are mentioned in Vitruvius and he states that they did not carry water as high as that achieved by water wheels. The effective maximum water depth of the Piscina is 8.4 metres, and the lifting height up to 11 metres, so the use of Archimedes Screws to remove water from the Piscina can be discounted.

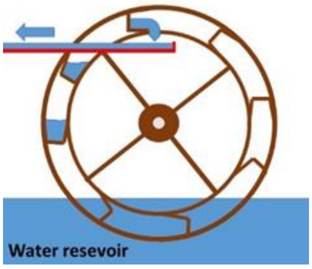

Figure 5 Water wheel

It would be conceivable to build a ***water wheel*** to lift water but to be able to extract water from the lower level of the Piscina the wheel would have to have a diameter of greater than the depth of the Piscina. The buckets need to be immersed in the water and the water collection channel at the top needs to be within the diameter of the wheel. As a result, to extract water from a near empty Piscina such a

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[16] To raise 1 kg of water by 1 metre requires 1 Joule of energy. Therefore to raise 2.5 million litres (a litre of water weighs 1 kg) would require a power rate of between 6.25 million, when the Piscina is full, and 27.25 million Joules, when empty, over a 24 hour period. To put this into a modern perspective, this task today could be done only by a powered industrial water pump operating continuously.

[17] http://www.romanaqueducts.info/technicalintro/waterlifting.htm discusses the types of water lifting devices available to the Romans.

water wheel would have had a diameter of about 12 metres, as well as having the capacity of raising 2.5 metric tons per day.

Although wood and iron (the materials available to the Romans) water wheels of over 20 metres have been built (i.e. a tourist attraction in Danzhai, China in 2017), the ability to build a wheel of 12 metres diameter and to operate it continuously was not known to be in the manufacturing capability of the Roman world. Even if such wheel could be built, and assuming 8 25-litre buckets spread round the diameter of the wheel, the 2,500 m^3 per day would require the wheel to be rotated, by man or animal power, at a velocity of over 17 revolutions per minute continuously over 24 hours. A task almost certainly beyond the capability of Roman industry.

Additionally, a water wheel needs a constant level of water at both the collection and distribution end, so a single water wheel could not have been used to extract water from the Piscina when the water level was constantly lowering. These three considerations also discount the possible use of a water wheel.

The Romans had limited **force pumps** (Oleson 2000) made from either wood or bronze and Vitruvius refers to the Pump of Ctesibius (a Greek inventor from Alexandria in the 3rd Century BCE). But such pumps were of limited size, capacity and power and would not have been able to lift 2,500 metric tons per day to any height, let alone one of 10 metres.

The option of man or animal powered raising of water in buckets is the only remaining option. This comes in two forms.

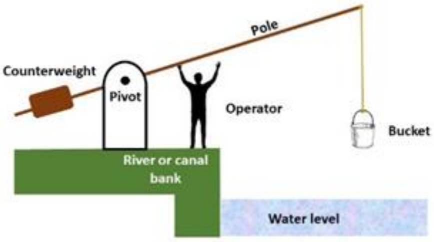

Figure 6 Shaduf

The simplest form is the ***shaduf***, a bucket on a rope at the end of a long pole mounted on a pivot with a counterweight on the opposite end. The bucket is lowered into water, usually an irrigation canal or river, then raised, the operator catches the rope, pulls it in and empties the bucket into the area to be irrigated. This system has been in use in Egypt for millennia, but it is impractical that it could be used to remove 2.5 million litres of water from a cistern in one day, even if the pole could be made long enough to reach the bottom of the cistern and multiple shadufs were installed.

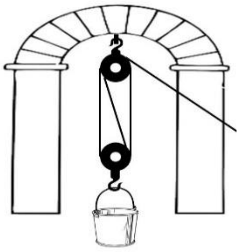

Figure 7 Bucket and pulley

The final option, of **buckets on pulleys**, appears to be the most practical. Single pulleys, man or animal powered, had been in use since prehistoric times, and complex (geared) pulleys are described by Archimedes in the 2nd and 3rd century BCE. It would certainly be possible to use these to remove water from the Piscina, but one must look at the amount of water required to be lifted. A bucket and pulley system, or even 10 such systems, assuming the roof was strong enough to support this amount of machinery, did not have the capacity to lift 2.5 million litres of water in a day, see calculations.[18]

All the above hydraulic engine solutions also ignore the question of how the water was handled once it was extracted from the Piscina, once the bucket-

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[18] Assuming the largest bucket of water that could be raised by slave or animal power contained 25 litres (and weighed 27-30 kilograms allowing for the weight of the bucket), it would take 100,000 full buckets per day to give the town its expected allowance of water. Even assuming 10 pulley systems built on the roof of the Piscina and removing water continuously, it would still take 10,000 single bucket extractions per system. If one allows a rate of 30 seconds per extraction, calculation shows that it would take nearly 3.5 days to extract the daily quantity of water needed from a Piscina when the water was at a low level. If the Piscina was full, the only parameter that changes is the height to which the buckets need to be raised and consequently the time taken. Assuming 15 seconds per bucket extraction and that 10 pulleys worked non-stop it would still take 1.7 days to extract a day’s worth of water. Therefore there are not enough hours in the day to supply the population of Misenum with water using “bucket and pulley” systems.

full of water was at the height of the roof of the Piscina. There were only two possibilities open to the Romans:

a. Build a pipe or water channel system, pour the buckets of water into it, and then pipe the water down the hill – in which case why not connect this system directly to the Piscina?
b. Load the water into barrels mounted on pack animals and carry it down the hill. Typically a mule can carry 100 kilograms, or 100 litres of water. It would therefore require 25,000 round trips to deliver the water requirement. At a very high 100 trips per day per mule there would have to be 250 animals with handlers working continuously.

The above calculations comfortably show that no hydraulic engine available to the Romans could have extracted water from the top of the Piscina, in the required volume and at the required rate, and distributed this volume to the population, baths and dockyards of Misenum. An alternative solution needs to be proposed.

6.6.2 The provision of water to Misenum

The Augusta Aqueduct flowed continuously into the Piscina Mirabilis day and night. The flow may have varied with the seasons of the year, or the amount extracted further upstream, and may have stopped entirely when there was damage upstream or when a part of the Aqueduct needed to be repaired. But the Aqueduct, and therefore the Piscina, operated on the principle of continuous input and continuous output. Both of these needed to be managed.

Roman culture expected a continuous flow of fresh water. This was provided by an aqueduct. It also expected that this water supply be uninterrupted and that it be at sufficient pressure and momentum to be manageable and to reach the extremes of its distribution network. This was provided by the Piscina.

When the Aqueduct was running at expected volumes the Piscina would be full. The water flow would simply “top up” the Piscina and continue to supply the needs of the town. This would be the normal and expected situation, “business as usual”. In this situation the Piscina is not needed.

When the water was running at very low volumes or had been cut off, deliberately or accidentally, the Piscina would be expected to make up the shortfall from its stored volume of water. This would be an abnormal and unexpected situation. In this situation the Piscina is essential.

As we have shown that extraction of water cannot be carried out by its removal from the top of the Piscina using mechanical means, the amount of water required by Misenum could have been provided only by continuous-flow devices, i.e. open channels or enclosed pipes, attached to the top (high-water level) and/or bottom (low-water level) of the Piscina. Other than in the central basin, no exit holes have been observed. However there is extensive repair work on all the walls including replacing bricks and applying cement so any holes, which would likely have been flush with the wall, could have been covered over.

6.6.3 High-level extraction – “business as usual”

The Aqueduct flow did not stop at the Piscina, it continued into the town of Misenum, a conclusion made by Sgobbo in 1938. Otherwise it would simply have overflowed. This route would have been either by the Aqueduct running in parallel to the Piscina or by the water entering the Piscina and being removed by an outflow at the same end of the Piscina.

The ***first*** option, shown as **Option A** in **purple** in Figure 9 and referred to here as the “in parallel” option, would be to have the main flow bypass the Piscina completely, flowing beyond it straight to a *Castellum Divisorium*, a Roman “junction box” (Hodge 2002) for water flow, where the supply could be divided between the various users of water: drinking water, baths, dockyards and industry, ornamental fountains, and where the supply to each constituent could be controlled and, if necessary, cut off. A side channel before the Piscina could then be used to keep the Piscina full, to “top it up”.

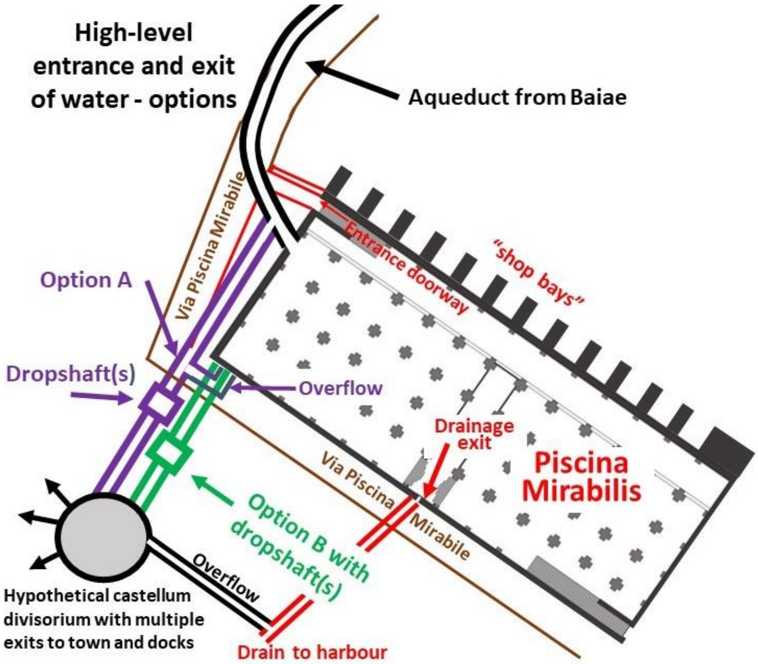


Figure 8 Two ways the Aqueduct could have connected with the Piscina

These *castella divisoria* are common at the end of aqueducts from Germany to North Africa, from Rome to Pompeii, and come in various forms and sizes (see Photograph 17 for an example. In this photograph the aqueduct flow entrance is the large rectangular aperture at the back. The various output holes are at the front). They are usually shallow open-air cisterns with an input source and multiple outputs, either pipes or open channels, each controlled by sluice gates, a device whereby it would be simple to regulate flow, or prioritise one user over another, by varying the height of the sluice, with something as simple as wooden boards, adding or removing boards as required (Hodge 2002).

An advantage of a castellum is that it provides a simple method of managing water between the various water user types. It is also simple to add new outlets.

Photograph 17 Castellum Divisorium in Nimes, France (Carole Radata, Wikimedia)

Examining the surrounding terrain as shown in Map 4 at the start of Section 6.4, the falling land southwest of the Piscina offers a suitable site for such a facility. Part of this area is built up but the eastern end closer to Misenum town is still used for small scale agriculture.

To move this castellum to the east would be difficult due to the high ground on the SW side of the Piscina, and any castellum would have to be excavated into the tuff rock. To move it further west would put it over falling ground towards the shores of the Inner Harbour. Given that the castellum would have to be 9-10 metres below the high-water level of the Piscina high-level output or of the Aqueduct input, and that the distance to the castellum would be no more than 15 metres, one or more dropshafts (vertical shafts designed to reduce the speed of flow and energy of the water, see Figure 9 in Section 6.6.4) would be required before the castellum to reduce kinetic energy and water velocity (Chanson 2002). As well as channels or pipes to the various water users, the castellum would still need an overflow capable of handling water surges, e.g. during winter rain.

The Piscina would also have to be kept full, so this option would have required a junction in the Aqueduct just before it reached the Piscina to allow water to be also channelled into the Piscina.

This junction could also be controlled by a sluice to, if required, cut off water from one of the two routes.

Regardless of the potential of diverting water at the above-mentioned junction, there would also have to be, within the Piscina and at a level slightly lower than the input channel, an overflow from the Piscina. This could be directed anywhere but, logically, would flow back into the main channel

The **second** option, referred to here as the "in sequence" option shown as **Option B** in **green** on Figure 8, is, on the face of it, simpler. All the water flow goes into the Piscina and it is taken out by an extract channel at the high-water level, logically on the opposite wall from the input to the Piscina. From here it would proceed to the *castellum*, again, if necessary, using dropshafts to reduce kinetic energy.

In both options A and B the channels marked in purple and green in Figure 8 could be simple rectangular stone channels as for the rest of the Aqueduct, probably following the same dimensions as the Aqueduct channels observed at the Baia Archaeological Park, 40 cm wide and 40 cm deep, with the maximum depth within the channel being 30 cm.

At the time of writing this paper, there is no firm opinion as to which of the two options would have been selected. Option A has the advantage that it allows the Piscina to be isolated and drained without interrupting the flow of water to Misenum. This would be expected to be done during the winter when water flows were high so that there would be little likelihood of the reserve supply of the Piscina being needed. But regardless of a channel "bypassing" the Piscina, an overflow channel from the Piscina would still have to be constructed to manage any excess; no engineer constructs a receptacle for collecting liquids without allowing for an excess of these liquids causing an overflow. But Option B is simpler as it requires less construction as, in this case, the normal flow of water out of the Piscina and the above-mentioned overflow channel are one and the same thing.

6.6.4 Low-level extraction – upstream problems with the Augusta

Either option still required the facility of taking water from the bottom level of the Piscina as, without this, and accepting that the removal of water from the top of the Piscina in sufficient volumes is not feasible, there is no way that Misenum would have benefitted from the volume of water stored in the Piscina, its back-up or reserve supply.

In order to take advantage of the back-up, and to maximise the amount of water that could be extracted from the Piscina, there would have to be a water exit aperture at the base of the Piscina. This is the method commonly seen in the Roman cisterns in North Africa (Wilson 2001). This low-level channel would flow to the *castellum divisorium* where it would use the same distribution facilities as the main Aqueduct flow (see Figure 9).

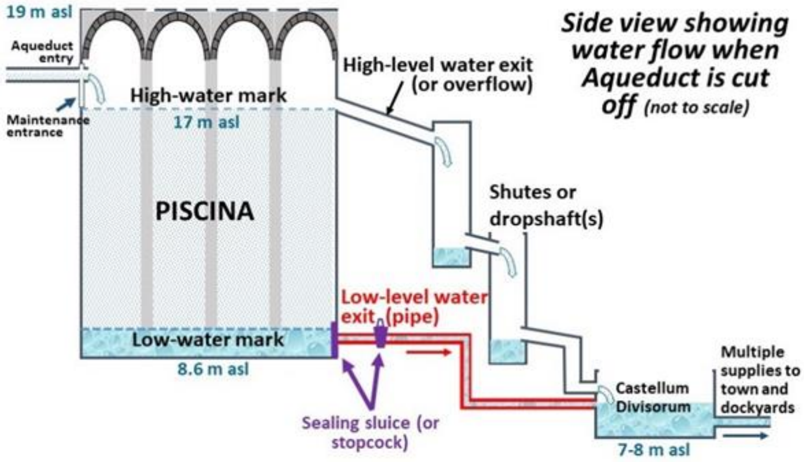


Figure 9 Side plan of the Piscina showing the water flow when the aqueduct was cut off

Would this low-level exit channel remain open or closed? If it was to remain permanently open, the cross-section low-level exit aperture, and therefore the flow, would have to be carefully calculated so that its volume capacity (m^3 per second) was less than that of the input from the Aqueduct whilst in operation. This was so that the low-level aperture did not extract water faster than it was input and so inadvertently drain the Piscina. At the same time it had to have enough capacity to provide water to Misenum when it was the sole source of water, i.e. when the Aqueduct was not providing water and the Piscina had entered its “abnormal” operation state.

Calculating a constant open pipe dimension is not possible as, firstly, although a figure of 2,500 m^3 per day is used, this would have varied significantly depending on the season and the usage. Secondly, the water pressure in the low-level exit pipe would decrease as the water level in the Piscina reduced when operating in the abnormal state. A method of closing off this channel, and consequently opening it on demand therefore becomes necessary (see Figure 10).

The simplest solution to closing off the aperture would have been a stone sluice gate (metal or a combination of wood and metal are also possibilities) which could have been laid flat against the aperture. Water pressure would have held the sluice gate in place and it could have been raised or lowered by means of ropes or chains from above, either via a maintenance walkway or through a hole in the roof suitably located above a side wall – see Photograph 5). This solution did not have to be watertight as the small amount of leakage around the side would be insignificant.

Closing the sluice gate could have been made more effective by installing grooves to hold it in place but none have been observed. Failing this positioning of the closure mechanism, the sluices could have been placed further down within the water channels, although this presupposes the ability to be able to access these stone slabs. Given that the southwest wall of the Piscina faces against solid tuff, this would have required extra access pits being dug to access these water channels. This is not a logically sensible option.

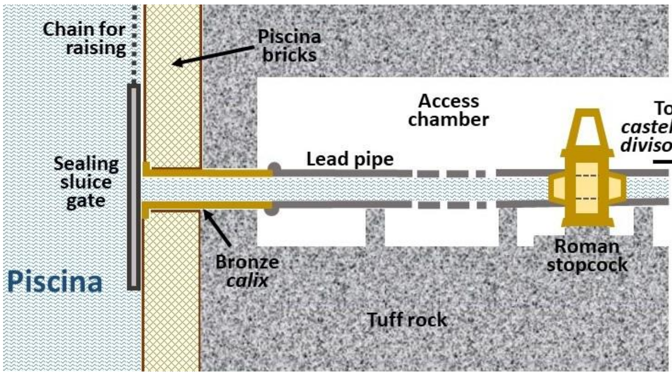


Figure 10 Low-level extraction from the Piscina showing the options of a sluice gate or a stopcock

This “emergency” exit, referred to as the low-level exit in this paper, would have used a lead pipe (or possibly earthenware but lead would have been more effective). A tunnel or access chamber would have to be dug through the tuff from the side of the Piscina emerging in the hillside above the possible location of the *castellum divisorium*. A pipe would then be laid connecting the Piscina to the *castellum* and the tunnel then closed off at the Piscina end and made watertight. It is possible a bronze *calix*, a hard metal nozzle or tube could have been used for the actual entry of the pipe into the Piscina (Frontinus; Hodge 2002) as this was standard Roman practice.

This pipe could then be closed off as required using a sluice gate, or, alternatively, a stopcock. Both are illustrated in Figure 10. Wilson (2001) observes that, in North Africa, in a similar situation, but 150-250 years later to what this paper is proposing for the Piscina Mirabilis, the low level outlets were controlled by stopcocks. Early stopcocks, also called taps or valves, are described in Hodge (2002) and in Lorenz (2013).

Photograph 18 A Roman lead stopcock from Baiae (Giovanni Grasso, Associazione Cocceius)

Looking at the benefits of both sluice gates and stopcocks, the sluice gate is a more likely choice. It is simpler and cheaper. Any stopcock near the Piscina outlet would have required a larger access chamber to be dug given the length of the turning bar that would be required on a large stopcock. Also, any such stopcock would have to handle the water pressure generated by the height of the water in the Piscina, some 8 metres of water pressure. Research (Lorenz 2013) indicates that Roman stopcocks would have difficulty withstanding a pressure of over 7 metres of water, especially as early as 27-12 BCE. The simple solution of a stone or metal sluice, held in place and self-sealed by the water pressure, and operated from above either from a walkway or via holes in the roof, is much more attractive to the engineer.

Either way, the effect of these sealing devices would be that the pipe operated in full on or full off mode. Adjusting a sluice gate that was many metres under water to enable a partial closure is infeasible, and Roman stopcocks operated only in full open or closed mode. There was no gradual opening as in a modern screw tap (Hodge 2002).

Where would the pipe be? There are two feasible options. The pipe would be close to the southernmost corner of the Piscina which would be closest to the probable *castellum divisorium* site, or, the outlet could be the visible southern output hole in the central basin.

Would there be more than one output pipe? It is possible that an output pipe could be located on the northern side of the Piscina to serve those villas in the valley between the Piscina and the Cento Camerelle. Only a small pipe would have been needed.

How big would the main pipe have to be? Based on the water flows a 9.4 cm diameter pipe would deliver normal service at the moment the Aqueduct was cut off. The standard 20-digit Roman pipe, equal to 10.2 cm diameter, would therefore be sufficient.

This was calculated as follows. The pipe would have to be big enough to deliver 2,500 m^3 per day (28.9 litres per second) at the point that the Piscina was full, and an acceptable percentage of this when it was near empty. Bearing in mind that the volume flow through the pipe would have decreased as the Piscina gradually emptied, three calculations were made:

a) ***What dimension of pipe would provide a level of water equal to "normal service" i.e. when the Aqueduct was running normally and providing 2,500 m^3 per day (28.9 litres per second)?*** Using the flow formula $A = V/(C_c \times C_v \times (2gH)^{½})$, where A = area of aperture/flow outlet (m^2), V = liquid volume flow in $metres^3$ per second (28.9/1000), g is gravitational acceleration, H is the height in metres of the water above the pipe, C_c is the discharge coefficient (a variable depending on the pipe aperture, a sharp edge aperture 0.62, well rounded aperture 0.97, this paper assumes a sharp edge), and C_v is the velocity coefficient of water (0.97). As $A = \pi \times (\text{Diameter}/2)^2$, it can be calculated that a 9.4 cm diameter pipe would deliver normal service at the moment the aqueduct was cut off. The standard 20-digit Roman pipe of 10.2 cm diameter would therefore be sufficient.

b) ***How long would it take to empty the Piscina assuming the pipe (dimension as above) was open all the time?*** By making iterative calculations at various depths it can be calculated that, if the above pipe was left open continuously it would empty the Piscina in approximately 5 days.

c) ***On the same basis as (a), what would be the flow of water to Misenum when the Piscina was half empty?*** By the time the Piscina was half empty, a 9.4 cm pipe would be delivering water to Misenum at approximately 21 litres/second, a drop of 28% of "normal service" volumes.

6.6.5 The central basin

The central basin, often referred to as the "drainage ditch" in the Piscina has always been considered a device for sedimentary collection or foreign matter, a "piscina limaria". It has two outputs, a large one covered in cement at the south end (Photograph 19),

Photograph 19 Output hole at the south end of the central basin

and a smaller circular one at the north end (Photograph 20). The purpose of both these outputs is still unclear.

The water source, the Serino springs, are 100 km away and the water flowed through channels coated in polished waterproof cement. Any debris which entered from the springs would not have reached the Piscina. Furthermore the Aqueduct was covered so vegetable matter is unlikely to have entered and, in any case, this could have been removed with a simple grid trap.


Photograph 20 The small, blocked, possible outlet at the north end of the central basin

The only sediment is likely to have been waterproof cement that had broken off, or flaked-off calx, deposited calcium carbonates. These deposits are heavy and dense. They would have collected at the bottom of the Piscina but there was no continuous flow to wash these into the basin. Whatever method that was used to keep the Piscina full, the "in parallel" or the "in sequence" options, would have been insufficient to keep a strong flow of water at the base of the Piscina, one strong enough to wash all sediments from the base of the Piscina into the basin. Furthermore the density of any sediment means that they were unlikely to have been flushed out. The output channels or pipes were more likely to compact the sediment in these outputs and block them completely.

The only solution, if a solution was needed, had to be to empty the Piscina, sweep particles from the base of the Piscina into the basin and then dig out the sediment by hand. If so what was the purpose of the basin and the possible output holes?

One must consider a possibility that the two holes visible in the basin are the exit holes for providing water from the Piscina to the population when the Aqueduct service was interrupted. The large southern hole would supply the town of Misenum, the smaller northern hole would supply the valley to the north of the Piscina. The basin could also have served to collect the small amount of cement and calcium particles that reached the Piscina and that this would be collected by first draining the Piscina, which incidentally makes the "in parallel" Aqueduct option the more likely, closing the output holes, sweeping any debris into the basin and then digging out any material by hand.

It is not possible to determine the function of this basin without extensive excavations to establish the size, direction, destination and possible function of the two outlet holes that have been observed.

6.7 Possible Piscina Management Procedures

6.7.1 In normal operation

Normal operation, "business as usual", is when the Aqueduct, at the point it reaches the Piscina, is running at a rate of 2,500 m^3 a day or greater.

Whether using Option A or Option B as described in Section 6.6.3, the bulk of the water flowing to the *castellum divisorium* for onward distribution to Misenum would be provided by the Aqueduct flow. In Option A, the sluice gate prior to entry to the Piscina would be managed to ensure a percentage of the water circulated through the Piscina.

It is important that the water in the Piscina be well aerated (oxygenated) and not allowed to stagnate so encouraging mosquitos and algae. Circulating water through the top level of the extreme northwest end of the Piscina alone would not be sufficient to do this. The Aqueduct and Piscina management teams, known as the *aquarii*, would have to ensure that water circulated in the depths of the Piscina as well as the far southeast end. This could be done by opening the low-level output pipe and allowing the level of the Piscina to drop before closing it again. The *aquarii* would be doing this on a daily basis, testing the depth and the water quality and balancing the water flowing in from the Aqueduct with the amounts split between the various exit routes.

6.7.2 During times of Aqueduct failure

There will have been times when the Augusta was not delivering sufficient water for the needs of Misenum. This could have been either reduced flow caused by drought affecting the Serino springs or unexpected extraction by the towns, villas and baths on the route from the source, or it could have been a total loss of water input – a deliberate act required by repairs to the Augusta or an accident such as collapse of a tunnel or cut and cover channel.

Regardless of the reason, the town of Misenum would now be dependent on the volume of water in the Piscina, the reserve supply. Management decisions would then step in. Was the problem known and likely to be fixed in a day or two, would there be a delay in ascertaining the cause of the problem, or was this known to be a major incident resulting in the closure of the Aqueduct for considerable time? Unlike Rome, Lyon, Nimes and other major Roman cities, there was only one aqueduct providing water. There was no option of another aqueduct making up the shortfall.

It would be expected that as soon as a problem was evident, the low-level output pipe would be opened so as to provide Misenum with its normal flow. There was no point in agitating the town for no reason. Decisions could then be taken on the basis of whether this was known to be an issue of a few days, or a few weeks. Leaving the low-level output pipe open would gradually reduce the water flow and the water level, and therefore the water pressure would be lowered. If this was not enough, water rationing would have to be introduced, such as switching off the water supply during the night. A low-level pipe was either on or off, there was no reduced flow option.

Would the Piscina be big enough? The Piscina can provide water for just under 6 days, more if water rationing is introduced. Regular maintenance, such as chipping away sinter, replacing concrete facing or repairing the foundations of cut and cover sections of the Aqueduct would be managed by the *aquarii* in 2 or 3 day spells. The Romans were able to cope with problems with a viaduct by introducing lead “bridges” (Frontinus). A major collapse of a cut and cover section could be repaired in a short time as a large number of labourers could be assigned, as could problems with siphons. The major issue would be a collapse in a tunnel as only one, or at most two, labourers could work on each tunnel face at the same time. A tunnel repair could therefore take months and Misenum would be reduced to living off its few wells (Blackman & Hodge 2001). This study could not find any accounts of this ever happened.

Very little is known of either aqueduct or cistern management in Roman times. Neither Frontinus or Vitruvius are helpful in the technical management of these, what the maintenance procedures were, how the *aquarii* were organised, or how supply management decisions were made.

7 From the Piscina into Misenum town and the dockyards

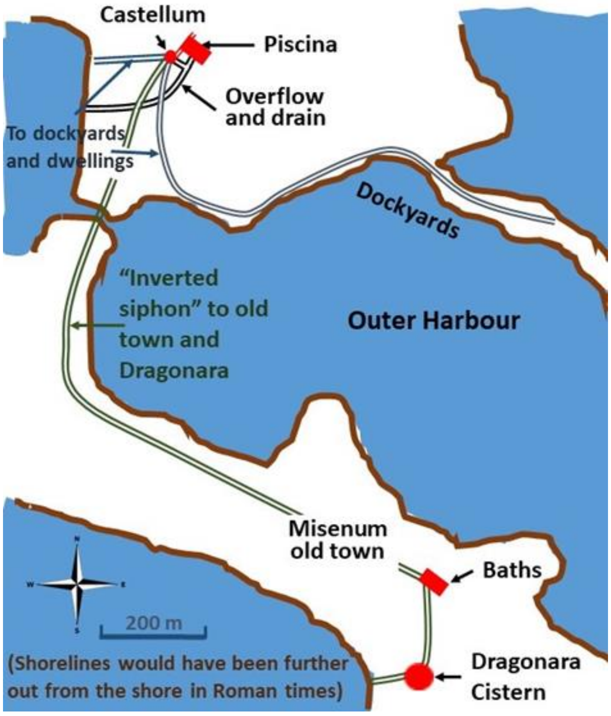
This section is hypothetical. Whilst there are elements of visual or logical evidence, enabling reasoned and logical inferences on the function of the Piscina, there is no such support for the water distribution system after the Piscina.

All that can be said is that there were dockyards for the construction and maintenance of naval ships, that there was a town on a peninsula across the Outer Harbour from the Piscina, and that this town had baths (remains exist) that all depended on considerable flowing water. There were also both drinking and decorative fountains, and there were high status private dwellings and public buildings (also existing remains). There must have been some form of water distribution system and what follows (see Map 5) is a proposal.

The *castellum divisorium* is already described in section 6.6.3 as the likely method of distributing water to the various users in Misenum. It is the most common type of distribution facility for Roman aqueducts and enables water to be channelled to the town, the baths, public fountains, private dwellings and the docks/ship maintenance sites. It is likely that, as is seen in Pompeii which had three main water supply networks (Olsson 2015), each of these users had their own distribution network. Water would be gravity fed from the *castellum*, operating as a “junction box” (Hodge 2002).

As well as pipes or channels to the networks, the *castellum divisorium* would also have the facility to regulate the water to each of the networks (Hodge 2002). Whilst an aqueduct was operating normally there would be no requirement to close or reduce flows to any of the networks. But when the aqueduct had ceased to flow, for whatever reason, and the town was dependent on the back-up supply contained within the Piscina, there was the need to close off or regulate the network. For example this may have been to reduce the flow to private dwellings or the shipyards, but to still keep the public water fountains operating. This could be done via sluice gates in the *castellum divisorium*.

Using a *castellum divisorium* would reduce the water pressure to that of the height of the *castellum*, but the convenience of a central distribution and control facility would have to be balanced against a reduction of water pressure due to the reduced height of the *castellum*. This should have been no major disadvantage. Water at a height of 7 or 8 metres was still sufficient to satisfy the continuous flow requirements of users such as the baths, docks and fountains, and was enough to drive the water down the approximate 1,600 metres to the far end of Misenum town. In fact, although it is probable that taps existed at Misenum[19], Roman taps could take only a pressure of around a head of 7 metres (Hodge 2002; Lorenz 2013) so a method would have to be found to reduce the pressure head of water from the 10 metres (the possible water level in the *castellum*) to acceptable levels. This could have been done using water towers (as at Pompeii), also called secondary *castella,* situated in the old town (Hodge 2002; Olsson 2015; Lorenz 2013)



Map 5 Possible water distribution to Misenum town

The routes to the docks, shipyards and any other industry situated in the areas immediately below the Piscina, to the west alongside Lago Miseno (the Inner Harbour) and to the south along the north side of the Outer Harbour and beyond to the Pennata docks, are relatively simple. This could have been achieved using open stone channels, pipes of lead or earthenware. It is also suggested, and this is conjecture, that the area on the east and north side of the Inner Harbour was the likely location for the homes of labourers and support personnel, so fountains would be important here.

The route to the old town, its baths, private villas and public buildings is more complex. An open channel, possibly on a low viaduct, would be possible, but this would be open to contamination and would lose all water pressure, pressure that is needed to drive water to the secondary *castella*, the decorative fountains, domestic cisterns and those possibly associated with the baths, as well as surmounting any small rises in the land. For these reasons it is suggested the water was conveyed along sealed lead pipes, in effect a shallow inverted siphon.

Given that the baths in Misenum are at a height of 8-9 metres above sea level, and that the ground in between is no more than a metre or so above sea level, any viaduct would have to be 7-

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[19] Taps and water valves (stopcocks) have been discovered in Pompeii and so definitely existed in 79 CE.

8 metres high and that means a double arch. Traces of such a construction are likely to have survived two millennia. In the case of a siphon, it is not surprising that no trace of the lead pipes remains given their considerable salvage value.

Whatever method was chosen there was still the problem of getting the water across the channel dividing the Inner and Outer Harbours. A siphon could follow a contour from just below the *castellum*, cross the channel at a height sufficient to allow the passage of ships, possibly with masts removed, then run at ground level, in one or more lead pipes mounted on concrete blocks as far as the baths, and possibly beyond into the Dragonara cistern. The solution could be a brick, stone or even wooden arch over the channel, carrying sealed lead pipes of the inverted siphon.

Illiano (2019) reports that the remains of a water channel into the Grotta Dragonara, a cistern at the end of Misenum town and under the hill of Cape Miseno, have been identified. This could be the overflow from the above system and the Dragonara overflowed to the sea.

Other than this possible input to the Dragonara, there are no identifiable remains of this network. Any stone work regarding the channels to the docks would long since have been reused in local buildings, and lead or earthenware pipes to water fountains and the extended piping to Misenum town would have been salvaged for reuse.

8 Questions, Conclusions and Next Steps

8.1 Outstanding questions

As in any piece of historic investigation, every discovery, every conclusion simply produces more questions. Some questions can be answered mathematically or logically, some are assisted by unearthed discoveries or from artefacts in museums, but some questions may never be answered. Only the finding of contemporary documentation, or at least documentation written soon after the event would answer these questions, and, as mentioned in the Introduction, there is little such documentation known, and, with the exception of one marble plaque, nothing specifically on the Aqueduct or the Piscina.

What follows are but a few of the outstanding questions.

8.1.1 Sequence of building?

Was the Aqueduct and the Piscina built, or at least planned, as a single integrated system? Or was the Piscina built afterwards once it was apparent that the Aqueduct alone did not supply sufficient water volume or pressure, and that, furthermore, its single channel was susceptible to a loss of supply? If the Piscina was built as a later afterthought, one also has to ask whether the final route of the Aqueduct, a high level viaduct, three or even 4 arches in height, necessary for the Piscina to be filled, was also built as an afterthought? It is unlikely this question will ever be answered failing the discovery of relevant ancient manuscripts.

8.1.2 Did the Aqueduct flow through or past the Piscina

Did the Aqueduct flow to the Piscina in sequence, i.e. did it enter and then flow out the other side? Or did it separate just before the Piscina with the main flow running alongside the Piscina (in parallel) and a short branch keeping the Piscina full? This is discussed in 6.6.3. Nothing has been noted on the upper parts of either the outer or inner walls of the Piscina. The “in sequence” option would have left few indications and the high level input and output channels would be common to both options and of the same size as the Aqueduct water channel cross-section. The channels necessary to the “in parallel” option have been obliterated by later building to the right of the entrance door, plus by the modern road. It is possible that excavation here would answer this question.

8.1.3 Location of output holes from the Piscina?

In sections 6.6 and 6.7 the requirement for water to be channelled out of the Piscina by continuous flow channels has been established. Water removal by hydraulic engines is not mathematically or technically feasible.

What has not been established is where these output channels were. The high level output referred to above would have left few traces, although one would have hoped to identify an output channel at the probable high water mark in the Piscina. The low level channels would have been pipes and in all probability were blocked and bricked or cemented over once the Aqueduct had ceased to provide water.


Photograph 21 Corner of internal SE wall showing repair work

A section of the lower part of the southeast wall of the Piscina is shown in Photograph 21. A thick bank of cement, a *pulvinus*, presumably *opus caementicium*, is shown at the bottom of the wall. This extends all the way round the Piscina. Above can be seen elements of *opus reticulatum*, part coverings of *opus caementicium*, 20th (?) century brick repairs, possible older repairs plus smaller areas that could be blocked holes.

Any output holes on this wall would have long disappeared. Bronze *calices* would have been salvaged and the holes filled in either deliberately or by accumulated debris. There is also the possibility, discussed below, that the output holes were those seen in the central basin.

8.1.4 The purpose of the central basin

The central basin in the Piscina has always, from Saint-Non in 1782 to recent authors, been referred to as a device for sedimentary collection or foreign matter, a “piscina limaria”. It has two outputs, a large one covered in cement at the south end, and a smaller circular one at the north end. The water source, the Serino springs, are 100 km away. Any debris which entered from the springs would not have reached the Piscina. Furthermore the Aqueduct usually was covered so vegetable matter is unlikely to have entered and would have been removed with a simple grid trap.

Known piscinae limariae, as seen in the aqueducts of Rome and, possibly, Germany are built in line with the aqueduct with a strong flow of water passing through them. There appears to be no benefit in having a piscina limaria in a side channel of the Aqueduct, one that would only have a significant flow when the Piscina was being emptied.

Is the basin a device primarily for the collection and flushing out of debris, or is it the location of the output holes from which water would be provided when the Aqueduct flow had been interrupted? It is possible ground radar could answer this question, failing that, excavation would be needed.

8.1.5 Why is the northeast side of the Piscina unsupported?

The Piscina is supported on three sides by the surrounding tuff rock. The exception is the NE wall where a thick wall supported by massive buttresses has been built. This appears unnecessary when one considers that, by moving the Piscina 15 metres further south, it could have been entirely supported by the surrounding rock.

However, when considering the actual construction, the positioning of the Piscina appears more logical. If the Piscina had been completely surrounding by supporting tuff, all the excavated waste rock would have had to have been removed via the top of the excavated hole. This extraction could have been by carts laboriously pulled up an internally created ramp, by using hand operated cranes, or, at the most basic level, having labourers carry baskets of rock up ladders. It would be far simpler, and quicker, to have an open side to the Piscina through which oxen carts could take the debris out and dump it (the lower land to the northeast of the piscine offers a suitable place for dumping waste rock).

Once the complete Piscina had been excavated, then a wall with its retaining buttresses could easily and quickly be built.

Again it is possible ground radar could answer this question, failing that, excavation would be needed.

8.1.6 What is the purpose of the elevated platform inside the NE wall of the Piscina?

Against the northeast internal wall of the Piscina there is an elevated platform approximately one meter high and five metres wide. There is no apparent hydraulic management purpose to this.

A hypothesis, building on 8.1.5 above, is that this is the foundation for the NE wall of the Piscina. When the Romans came to build the retaining wall they would have had to provide substantial foundations for this. Tuff is less dense than granite or limestone and, especially if broken rocks mixed with softer earth, would be unsuitable as foundations for a substantial wall. The solution would be to create a platform using tuff rock (from the excavation) mixed with cement and, possibly, more substantial rock debris either brought in or left over from the building of Misenum town and its dockyards. This would then provide a robust foundation for both the wall and the buttresses. Extending this foundation into the Piscina would avoid any tendency for the foundation to subside or tilt. There was no need to embed this foundation into the ground as that would have required a higher wall and buttresses. The elevated foundation becomes part of the retaining wall.

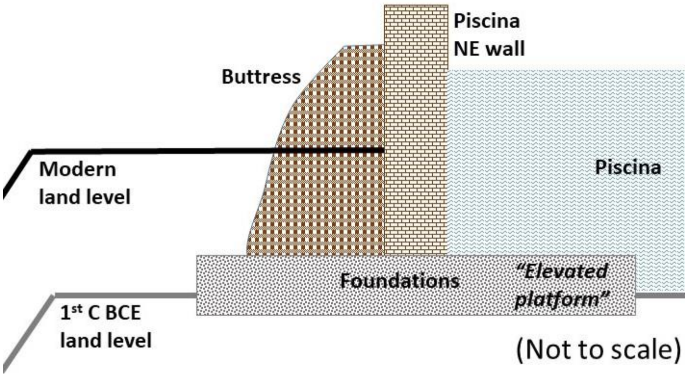

Figure 11 NE side wall

Again it is possible ground radar could answer this question, failing that, excavation would be needed.

8.2 Authors' Conclusions

A summary of the major conclusions of this paper are as follow:

A. The Augusta Aqueduct was needed to fill the Piscina Mirabilis. It would have crossed Bauli, the modern town of Bacoli, on an elevated viaduct, would have approached the Piscina along the ridge between the Sant'Anna church and the Piscina, and entered the Piscina on the northwest corner at an angle of approximately 45 degrees.

B. The Aqueduct did not terminate at the Piscina Mirabilis but ran beyond this, either through or alongside the Piscina, to a *castellum divisorium* where the water flow would have been divided between the various water user types in Misenum.

C. That the Piscina Mirabilis served as a water storage device, a backup, designed to provide water - to the dockyards of the Inner and Outer Harbours, to the dwellings in Bauli on the east side of the Inner Harbour, and to the old town of Misenum - at times when the Aqueduct was not running or running at a reduced rate.

D. That there were no hydraulic devices extracting water from the roof of the Piscina Mirabilis. When the Aqueduct was running normally, water was directly channelled to a *castellum divisorium*. When the Aqueduct was not providing sufficient water, the *castellum divisorium* would receive water via pipes from lower parts of the Piscina.

E. A castellum divisorium, similar to those at Pompeii and Nimes, would have been located in the lower ground just beyond the south west corner of the Piscina. From there it would have had water connections to the old town of Misenum and the dockyards on the south side of the Outer Harbour, most probably via an inverted siphon, to the dockyards and dwellings on the east side of the Inner Harbour, and to the dockyards on the north side of the Outer Harbour.

F. The function of the central basin at the bottom of the Piscina is unclear. Is it for the collection of debris, or is it the source of the supply of water to Misenum when the Aqueduct flow had been interrupted? This paper identifies the possibility that it was the exit point of the "emergency" low level output pipes and that the collection of debris was secondary.

G. The elevated platform against the internal NE wall of the Piscina is part of the foundations of this wall.

8.3 Next steps

There are many hypotheses in this paper. In many cases, engineering logic has been applied and it would be beneficial to be able to back these with more archaeological field work. Areas suggested for further research are:

a) Using ground radar, examination of the tuff rock ground southwest of the Piscina for any tunnels which may have carried the drainage exit and the low level exit pipe(s), also the horticultural area just beyond this to seek any traces of a *castellum divisorium* and its input and output channels (see Section 6.6.3);
b) Also using ground radar and thermal imaging to examine the internal walls of the southwest corner of the Piscina for any traces of output pipes (see Section 6.6.4), also the blocked exits (pipes?) which can be seen at either end of the central basin;
c) Analysis of the waterproof cement on the internal walls and pillars of the Piscina with particular regard to trying to establish which cement that is originally Roman and that which may have been applied at later dates including the 1920s restoration, and establishment of the height to which the original cement reached. Also analysis of the brickwork to differentiate Roman from more modern bricks and to confirm all bricks, other than tuff ashlars, used are kiln-fired;
d) Excavation at the NE wall to establish the depth of the buttresses and the foundations of the wall. This has a benefit of being able to be carried out without any damage to the Piscina itself
e) Further exploration of the Roman baths at Misenum to establish their water supply and the flow direction of any channels between the baths and the Piscina, or the baths and the Grotta Dragonara (see Section 7).

Further research the libraries of the Parco Archeologico dei Campi Flegrei, the Museo Archeologico dei Campi Flegrei nel Castello di Baia, the Archaeological Museum of Naples (MANN) and the British Library to look for further accounts from the 5th to early 20th Centuries which mention the Piscina and Aqueduct. Any discoveries of Roman scripts, plaques or carvings relevant to the Augusta Aqueduct or the maintenance of aqueducts in general would be of great interest.

Resources have been and still are limited and the Covid-19 pandemic continues to create problems. The authors would welcome others investigating the above areas and would be happy to collaborate on this.

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