Cross-Disciplinary Investigation of Ancient Long-Distance Water Pipelines

by

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M.Sc., Carl-von-Ossietzky Universität Oldenburg, 1996
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Abstract

This dissertation demonstrates how the cross-disciplinary application of methods and tools from archaeology, philology, and engineering can yield insights into ancient water-supply systems and help to solve problems associated with their precise function and with their description in ancient literature. Conventional calculations determine the flow properties of seven ancient long-distance pipelines. Components of the water-supply pipeline at Aspendos are simulated with a commercially available Computational Fluid Dynamics (CFD) software package (FLUENT® by Fluent Inc.) that is widely used in the design and research of complex flow systems. The application of CFD clarifies the interaction of water and air during the filling process of a pipeline. The project establishes a methodology using state-of-the-art computer simulation tools for the investigation of these systems. The combination of the numerical results with the insights derived from a comparison of Latin technical documents with ancient Greek medical texts answers conclusively some long-term questions that have been plaguing aqueduct research for a long time. The simulation makes visible the flow of water in the pipeline, disproving the long-term misunderstanding that entrained air will form bubbles in the flowing water column that lead to pressure transient. It is possible to explain the function of lateral holes in the sides of pipe segments. The calculated volume flow rates for each pipeline allow estimates about the population sizes for the cities supplies by the aqueducts. The creation of a computer-based methodology for the study of ancient aqueducts will enable scholars to investigate, compare, and catalogue a wide variety of ancient hydraulic systems.

Table of Contents

List of Tables

List of Figures

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Abbreviations

In spelling the names of Greek authors and their works I have followed Liddell, Scott, and Jones *Greek-English Lexicon* (Oxford 1968); for Latin authors, the *Oxford Latin Dictionary* (Oxford 1983). For authors not in either of these works, and for abbreviations of modern reference works I have followed the practice of the *Oxford Classical Dictionary* 3rd ed. (Oxford 1996). Monographs, book sections, and articles have been cited by author and date, and the full titles can be found by consulting the bibliography. The abbreviations of periodical titles are those of *L'Année philologique*. In addition, the following abbreviations appear:

CAH	*Cambridge Ancient History*
CFD	*Computational Fluid Dynamics*
CIG	*Corpus inscriptionum graecarum*
CIL	*Corpus inscriptionum latinarum*
IGRP	*Inscriptiones graecae ad res romanas pertinentes*
LCL	*Loeb Classical Library*
OCD	S. Hornblower and A. Spawforth, edd., *Oxford Classical Dictionary*, 3rd ed. Oxford: Oxford University Press, 2003.
OLD	P. G. W. Glare, ed. *Oxford Latin Dictionary*. Oxford: Oxford University Press, 1983.
PECS	R. Stillwell, ed. *Princeton Encyclopedia of Classical Sites*. Princeton, NJ: Princeton University Press, 1976.
RE	A. Pauly, G. Wissowa, W. Kroll, *et. al.*, edd. *Paulys Realencyclopädie der classischen Altertumswissenschaft: neue Bearbeitung*, Stuttgart: J. B. Metzler, 1894-.
TLG	*Thesaurus linguae graecae*

1. Introduction

Water is best, states Pindar (*Ol.* 1.1), and Plato agrees (*Euthyd*. 304b). Tantalus' eternal thirst is the punishment for the archetypical sinner (Homer *Od.* 11, 583-7). Zeus wipes out all of mankind in the Deucalian Flood (Ov. *Met*. 1.260-415). Heracles diverts the water from the Alpheus and Penius Rivers to clean out the Augean stables (Apollod. *Bibl.* 2.5). Ancient myths demonstrate the usefulness of water as well as its dangers when it is lacking or when it is overabundant. In the book of Exodus (7.14-24) the water of the Nile, the very source of existence for Egypt, turns to blood. In Isaiah (41.17/18; 43.20) the Lord renders the desert habitable for his chosen people by opening rivers, fountains, pools and springs.

Attention to water is equally prominent in ancient natural philosophy. For Thales of Miletus water is the primary constituent of all matter (Aristotle *Metaph*. 983 b6). Hippocrates (*Aer.* 7-9) is aware of the influence of water supply on human health, as are Aristotle (*Pol.* 1330 b) and Plato (*Leg*. 747 d, e). There is no doubt that both biologically as well as conceptually water is vital for the life of a society. Quite often, however, a water source is located at a place where, for lack of defensibility or because of poor communication, the building of a settlement is not advisable. Conversely, sites that are in other respects favorable for the construction of a settlement frequently lack a reliable natural supply of water. As a result, a sufficient amount of water must be transported to the settlement from elsewhere. The transport of water can be a very laborious task—a notion that finds expression in the myth of the Danaids who are forced to carry water in leaky containers in the underworld as punishment for the murder of their husbands (Pl.

Ax. 371 e; Pl. *R*. 363 d). Water is heavy due to its density, one kilogram per liter or one metric ton per cubic meter to be precise. In addition, liquid water is viscous and extremely amorphous. These physical properties make containment and transport of water a challenge in terms of material and energy requirements.

The earliest and most basic container for water was without doubt the cupped human hand (*Judges* 7.5-6; Verg. *A.* 6.66-78), followed perhaps by gourds, the shells of shellfish, or the sheaths of bovine and caprid horns (Oleson 2000: 219). The material used in antiquity for the manufacture of large and small water containers could be terracotta for *hydriai*; glass for cups, goblets, and bottles; base or noble metals such as lead, copper, bronze, silver, or gold for cups and cauldrons. Larger containers, such as buckets or wine casks, could be made of wood, or of stone such as cooking pots or troughs for the watering of animals. Leather skins were also used as water containers.

In vessels of this kind, water could be transported only in limited quantities, and overland only by means of animate energy sources, *i.e.* humans or animals. Such containers, made of any material, have common disadvantages: the containers must be transported together with the water. They add to the weight that needs to be carried; some are prone to breakage (terracotta) or rot (wood); for a purpose that inherently bears the risk of breaking or otherwise losing the container, the material may be too pricy (metal) or too rare or too difficult to shape (stone).

The partial solution to these disadvantages is to create vessels in the forms of channels or stationary pipes and move only the water within. Instead of humans and animals, hydrostatic pressure, which is due to gravity, and is a form of energy that is nominally free, universal, and continuous, requires no fuel, attention, supervision, or rest, can be used to drive the water. The obvious disadvantage is the requirement of large quantities of metal, stone, terracotta, or wood for the manufacture of channels or pipes.

This dissertation sets out to answer the same questions that Trevor Hodge intended to answer in 1992: “How did an aqueduct really work?” (Hodge 1992: vii). The question seems trivial. Experience teaches us that whatever fluid enters a conduit at one end comes out at the other end, unless there is a leak somewhere. But in reality, flowing water does not behave as straightforwardly as this idea suggests. Changes of gradient in an open channel from steep to shallow, for example, cause a phenomenon known as hydraulic jump, where transition between tranquil (or sub-critical) and rapid (or supercritical) flow regimes occurs. Hydraulic jumps may cause damage to the conduit surface through erosion. Interaction between residual air and water in pipelines may cause problems to an extent that the system becomes useless. Ancient designers must have been aware of these dangers. They also must have known how to avoid them; otherwise ancient literature would contain more references to dysfunctional water supply systems. To be sure, ancient sources such as the inscription of Nonius Datus, or Frontinus’ *De aqueductu* as well as Vitruvius’ *De architectura* mention various problems with respect to the design of aqueducts. But they also give the impression that individuals in charge of such projects knew how to bring their tasks to successful completion. Some aqueducts have features that appear to have been the designers’ response to some technical problems. The remains of the aqueduct towers at Aspendos and at Yzeron have led to decades of speculation among modern researchers regarding the physical problem they may have solved. Other pipelines, such as at those at Pergamum, Smyrna, and Alatri, were deliberately laid out to incorporate intermediate hills into their course. No modern scholar has conclusively explained the reasons why the ancient designers chose to include intermediate man-made or natural high points into some of their long-distance pipelines. Vitruvius, Pliny the Elder, and Frontinus have been studied carefully in search for the function of these high points, but without significant success. The investigation of the pipelines associated with these aqueduct systems has until very recently fallen into the gap between the disciplinary boundaries of ancient history, archaeology, and engineering.

This research project employs computational fluid dynamics (abbr. CFD) a tool that was not available to Hodge one and a half decades ago: Only Ortloff (1998; 2001; 2003; 2005) has applied computer simulation to the investigation of ancient hydraulic structures. The approach is novel, but it has its limitations. The CFD-software that is commercially available has not been conceived to investigate ancient aqueducts that are several hundred meters long, but rather to simulate and optimize smaller-scale flow processes in modern industrial and environmental applications. The size of ancient aqueducts is a challenge in terms of computation time. Moreover, the simulation of turbulent flow and the tracking of an air-water interface are particularly knotty problems in fluid mechanics and CFD-research. But as computer capabilities are improving, it is possible and necessary to explore this frontier of research and test its applicability to questions that archaeologists and historians of hydraulic technology ask.

The CFD-model initially simulates the well-studied aqueduct at Aspendos, in order to establish a meaningful and efficient methodology. Ideally, the results for flow velocities, pressures, and resulting forces, arrived at by means of conventional methods would have served as a benchmark for the accuracy of the computer model. The size of the computational domain, however, in conjunction with the time constraints of the dissertation made it necessary to reduce the scale of the model to 1:10 for the vertical coordinate and 1:20 for the horizontal stretches, while maintaining the original pipe diameter. Unavailability of the computer cluster for extended periods of time due to maintenance and hardware malfunctions further complicated the study. Nevertheless, the simulation of the pipeline on a reduced scale was successful and has shown that the method is transferable to full-size aqueducts, given sufficient time and assuming that computers will be more powerful in the future. Once the reliability of the method is confirmed, it will be possible to apply it to less-well studied aqueducts. The pipeline at Segóbriga in Spain is an excellent test case. I created the model of the pipeline at Segóbriga, also at a scale of 1:20, but the difficult circumstances of the computer availability did not allow me to run a simulation of this model. Further candidates are aqueducts at Smyrna and Alatri. Sufficient information about the dimensions of these aqueducts is available from previous research. The Hellenistic aqueduct at Methymna, on the island of Lesbos, needs to be surveyed, in order to make it a candidate for future simulations. The primary long-term research outcome will be a catalogue of simulations for a number of ancient water supply pipeline systems, summarizing and comparing their size, layout and flow properties. These simulations will answer Hodge’s question about how aqueducts of this particular type work.

It is important to recognize that there are several pipelines from antiquity that share the feature of intermediate high points. These high points are related to physical problems common to all of these aqueducts. What exactly these problems are is not precisely known. A first step to recognizing the problems is a collection and comparison of the physical properties of the pipelines. Such a catalogue will, moreover, contain valuable information useful for estimating population sizes, for investigating the exchange of information and technical know-how necessary for the construction of the systems, and for comparing individual solutions to particular difficulties posed by the topography to a successful water supply. Ancient aqueducts can be broadly subdivided into two categories: channels and pipelines. In a channel water flows with a free surface at atmospheric pressure. In a pipeline water may also flow with a free surface. But if the pipeline dips below the hydraulic gradient—a concept that Figure 1.1 illustrates—the water will ordinarily occupy the full cross-section of the pipe and be under pressure.

When an intervening valley between the source and the point of consumption was either too wide or too deep to be crossed by means of an arcaded bridge, the ancient designers often chose to cross it by means of a pipeline. This type of aqueduct consisted normally of a free-surface conduit that brought water from a source some distance away to a header tank at the edge of the valley that needed to be crossed. From the header tank one or more pipes led the water out and down the slope of the valley. Along the valley bottom the pipeline either followed the topography or was slightly elevated on some level substructure. On the opposite side of the valley the pipeline was brought up the slope again and fed the water into a receiving tank from where it was distributed to the consumers. Such a structure is customarily called an inverted siphon (Fig. 1.1).

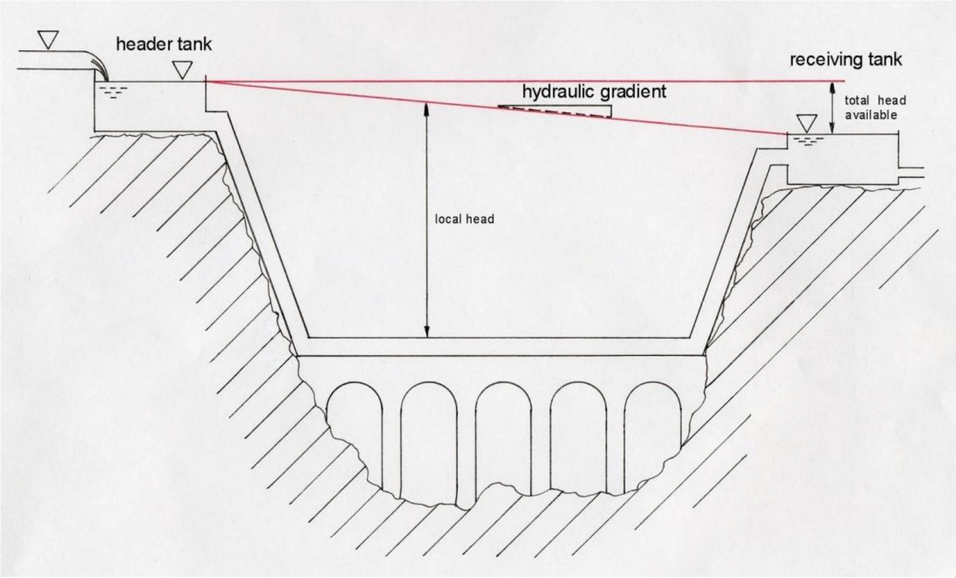

Figure 1.1: Schematic Layout of an Inverted Siphon

The focus of this thesis is on seven structures that contain such pipelines. The term “inverted siphon” has been criticized in the past on the grounds that a true siphon functions according to an entirely different physical principle (Smith 1976: 51; Hodge 1983: 174-80). But modern books on civil engineering use the term inverted siphon, too (Inversin 1986: 71). A true siphon consists of a usually flexible tube bent in the shape of an inverted U. It conveys a liquid from one vessel to another one that is located at a lower level by means of differential static pressure in the two legs. An inverted siphon, too, consists of a bent tube or pipe through which a liquid is conveyed from one vessel to another. The difference is that in a true siphon the pressures involved are below atmospheric pressure, while in an inverted siphon they are above atmospheric pressure.

The towers that were built, at considerable expense in material and labour, into the pipelines of imperial Roman inverted siphons at Aspendos in Turkey and Yzeron in France have puzzled researchers for over a century. In the mid-1980s Hodge edited four issues of a privately circulated newsletter entitled “Siphon Notes” and “Aqueduct Notes” in which some 40 scholars from all over the world exchanged ideas pertaining to these interesting structures. Despite the high quality of most contributions it has not been possible to combine them into a synthesis that embraces findings from all disciplines.

Until the 1990s, nobody had attempted to calculate the physical flow properties of these systems in order to get tangible quantitative results. A notable exception is the work done by researchers from the Institute for Hydraulic Engineering at the University of Braunschweig. Under the direction of Günther Garbrecht they surveyed the extensive water supply system of Pergamum and published in the series *Mitteilungen des Leichtweiss-Istitutes für Wasserbau* between 1973 and 1983 seven reports treating a wide range of topics such as system dimensions, flow properties and building materials. Recent groundbreaking work on the Aspendos aqueduct approached the problem from an engineering perspective and seemed finally to have brought the long-sought answer to the purpose of the towers (Kessener 2000a: 125-9). Kessener quite rightly states that the towers located at the bends in the pipeline at Aspendos reduced static pressure and, therefore, eliminated lateral forces that, if unchecked, would have had the potential to destroy the pipeline at those points. Kessener, furthermore, mentions the problem of water hammer, pressure transients, induced through air-water interaction, that travel through the water in the pipeline and can reach large, potentially destructive magnitudes. Subsequent queries by Deane Blackman and Yehuda Peleg regarding the conclusions of this most recent investigation show, however, that the fog has not yet entirely lifted (Blackman and Peleg 2001: 411-14). Blackman points out Kessener’s misunderstanding of the nature of water hammer and denies that forces generated by static pressure could damage the pipeline at a bend. He states, furthermore, that open tanks at the top of the towers at Aspendos would have done away with the problem of air pockets altogether (Blackman and Peleg 2001: 413). Peleg denies the existence of water hammer as a problem at Aspendos, and states that lateral forces from static pressure could have been checked much more economically simply by reinforcing the pipeline at ground level instead of building towers (Blackman and Peleg 2001: 413).

It has been recognized that similar features were included in various pipelines in response to different local requirements at a number of different sites (Lewis 1999; Kessener 2000a: 125-6). As a result, an investigation of the hydraulic towers must incorporate a direct comparison of a number of similar structures. At least seven aqueducts with intermediate high points are known to date: Aspendos, Pergamum, Smyrna, Yzeron, Alatri, Segóbriga, and Methymna. These aqueducts were built at different times and were laid out in response to varied conditions imposed by topography and building material.

This project has a number of objectives. One aim is to lay the ground work for a numerical analysis of a large number of inverted siphons. The long-term plan, beyond the dissertation, is to use Computational Fluid Dynamics (CFD) software to simulate ancient inverted siphons and put together a catalogue of their dimensions and key properties. This project tests the applicability of CFD to ancient aqueducts and investigates possibilities and problems. Conventional pencil-and-paper analyses of six pipeline systems (*sans* Methymna, for which not enough information is available) that are very similar and equally problematic in layout form the main body of the project. In each of these cases the ancient planners have deliberately brought the water up to or close to the level of the hydraulic gradient, by means of towers somewhere along the line in the first two cases, or by laying the pipeline across the summits of intervening hills. Results from previous calculations done on three systems, Aspendos (Kessener 2000a), Yzeron (Burdy 2002a), and Pergamum (Garbrecht 1978), already exist. These results serve as *comparanda* for the results of the present analysis.

Another objective is a new interpretation of Vitruvius' relevant passage on the layout of water pipelines in *De architectura* 8.5-8, which for a long time has caused difficulties to translators and commentators due to a lack of understanding of the technical principles involved. It is necessary to compare the vocabulary in the Vitruvian passage with that in relevant texts by Pliny the Elder, Hero of Alexandria, and the Greek writers of medical treatises. This dissertation is innovative in its approach, as it combines research tools from archaeology, philology, and engineering to bridge these disparate disciplines to the benefit of each of them.

The amount of information necessary for a physical analysis of an inverted siphon is extensive. The overall layout of the system must be known in detail, including its total length, the positions, opening angles and radii of curvature of bends and curves, the slopes of descending and ascending branches, the elevation above ground, the shape of the pipe's cross-section, the internal diameter of the pipe, its material, the number of pipes in parallel, the positions and depths of header and receiving tanks as well as the presence and position of armatures such as valves, pipe junctions or open basins. For six of the seven aqueducts listed above sufficient information of this kind is available. The aqueduct at Methymna has not yet been surveyed. There is a need to study and map the remains of the poorly-preserved aqueduct.

The results of these analyses can in the future be applied to what we know of the overall water systems at the sites in question. Does the more accurate knowledge of the potential capacity of the pipelines affect previous hypotheses concerning water use and population? Were similar procedures and solutions tried at a variety of sites, suggesting the exchange of technical ideas through personnel or written handbooks? It is my hope that the results from this dissertation contribute to the answer of these questions.

2. Survey of Ancient Literature

The storage and the exchange of information are prerequisites for the successful completion of large-scale engineering projects. The achievements in civil engineering in the Greco-Roman world could not have succeeded without written transmission of information, design blueprints, etc. It is unimaginable that aqueducts were built with the limited pool of information available in the memory of only one generation of craftsmen and engineers along with a solid tradition of trial and error. These structures can be a result only of the accumulated experience that generations of specialists stored in technical manuals. Only a limited number of ancient literary sources that deal with water supply technology have survived. Among these, Frontinus, Pliny the Elder, Vitruvius, and Hero of Alexandria are of particular importance. Other ways of transmission of technical know-how are discussed by Oleson (2004: 66): “Some crafts, such as ship construction, relied on such complex sets of information that […] direct transmission of techniques and designs from master to apprentice seems the only solution.” It is conceivable that the precise trade secrets of the aqueduct builders were jealously guarded and were not divulged to outsiders, which would explain the paucity of written material. The ability to convey water over long distances is, after all, important not only from a practical aspect, but also in terms of prestige and power. Whoever commanded the skill, whether as builder or as patron, had access to a source of high prestige. Although there is no evidence for protectionism of this kind from the Greco-Roman period, such practices were common among master masons in the fifteenth century (Gimpel 1976: 141). In this chapter I present a survey of ancient authors and texts that are relevant for the investigation of inverted siphons. These texts provide vital information about the theoretical knowledge that the engineers of antiquity had of the physical phenomena with which they dealt in practice. By studying a number of select examples, this chapter also investigates the problems encountered in translating ancient technical terminology into English and the difficulty of transposing notions from ancient natural philosophy into the framework of modern science and engineering.

2.1 Marcus Vitruvius Pollio

Only few details of Vitruvius' life are known. He was born probably about 80 or 70 B.C. Textual references to Octavian and to existing buildings in Rome indicate that *De architectura* was written in the 20s B.C. Vitruvius may have been involved with the *cura aquarum* as engineer or administrator under Agrippa after 33 B.C. and may have written his work drawing on his own professional experience (Callebat 1973: x). Book 8 of *De architectura* deals with a broad range of aspects of water technology. Vitruvius gives advice for finding a spring and bringing it to the *castellum divisorium* in the city. The text stops short of describing the intra-urban water distribution system.

Books 1-7 of *De architectura* deal with architecture as such. Books 9 and 10 are concerned with engineering topics such as clocks and various kinds of machines. Book 8 treats a topic intermediate between architecture and engineering. Callebat (1973: ix) suggested, therefore, that these parts of *De architectura* were written at different times and that book 8 was added to the ensemble only at a later date.

Chapter 8.6 specifically deals with aqueducts. If we ignore fleeting references by non-technical authors such as Statius (*Silv.* 1.3, 66-7), *De architectura* contains, next to Pliny (*NH* 31.57-8), the only surviving ancient literary description of inverted siphons. Vitruvius' description is notoriously difficult to translate and has caused much discussion among modern scholars, to the point that Smith (1976: 58) suggested that “it is possible that Vitruvius did not fully understand his material himself”, a sentiment echoed by Garbrecht (1987b: 18). Attempts at reconciling the text with archaeological evidence create additional difficulties (Millette 1997). Vitruvius’ text does not exactly match the remains of surviving pipelines. That does not imply, however, that Vitruvius did not understand what he was writing about. Technologies and techniques change through time and are adjusted to regional requirements that may be particular to only one specific site with its individual problems. The sample size of surviving inverted siphons is too small to allow a comprehensive reconciliation with Vitruvius’ text. Furthermore, the physical problems of gravity-fed water pipelines are so complex that today, too, their investigation is conducted by means of problem-oriented models (Gandenberger 1957). Lewis (1999: 171) has pointed out that Vitruvius wrote not about Roman, but about Hellenistic aqueducts, while most of the surviving archaeological evidence is Roman (Hodge 1992: 428, note 43). Kessener’s (2002b) article, which ascribes to Vitruvius a thorough knowledge of air-water interaction in pipelines, goes, in my opinion, too far. The behavior of air bubbles in water flowing in inclined pipes is very complicated, and research into this phenomenon requires either transparent pipes or computer simulations (Winkel 1914; Gandenberger 1957; Schnappauf 1966; Kottmann and Schmitt 1980; Knauss 1983; Kottmann 1984b; Baines and Wilkinson 1986; Kottmann 1992). Since neither was available in antiquity, it is unjustified to ascribe to Vitruvius and his predecessors precise knowledge of a phenomenon that was essentially invisible and not quantifiable to them, and which remains a challenging fluid dynamics research topic to this day (Ohnuki and Akimoto 2000).

Individual key terms from the relevant passages in *De architectura* need to be interpreted differently than they have been in the past. A refinement of the meanings of *geniculus* and *libramentum* can bring out particular facets of Vitruvius' text that have been overlooked. I suggested previously a new translation of the relevant passages from Vitruvius (Nikolic 2003), which I present here with further refinements. The Latin text is from the Loeb edition of Vitruvius, unless otherwise indicated. The translation is my own.

> 5. Ea autem ductio, quae per fistulas plumbeas est futura, hanc habebit expeditionem. Quodsi caput habeat *libramenta* ad moenia montesque medii non fuerint altiores, ut possint interpellare, sed intervalla, necesse est substruere ad *libramenta*, quemadmodum in rivis et canalibus. Sin autem non longa erit circumitio, circumductionibus, sin autem valles erunt perpetuae, in declinato loco cursus dirigentur. Cum venerit ad imum, non alte substruitur, ut sit *libratum* quam longissimum; hoc autem erit *venter*, quod Graeci appellant *coelian*. Deinde cum venerit adversus clivum, ex longo spatio ventris leniter tumescit; exprimatur in altitudinem summi clivi. (*De arch.* 8.6.5)

> 5. That line, however, that will be made of lead pipes will have the following setup. But if it has the head on the same level as the city walls and the hills between them are not higher so that they might interfere, but if there are valleys in between, it is necessary to build a substructure to the level in the same manner as for channels and canals. If, on the one hand, the deviation [around the valleys]

> will not be long, the course will be directed on a circuitous route. If, on the other hand, the valleys are continuous, the course will be directed in a lower location. When it has arrived at the bottom, a substructure is built, but not a high one, in order that the level stretch is as long as possible; this, then, will be the *venter*, which the Greeks call *coelia*. Then, when it has come to the facing slope, it slowly swells out of the long extent of the *venter*; it is pushed out to the height of the top of the slope. (trans. Nikolic)

The term *libramentum* in this passage is generally translated as incline, slope, fall, or gradient, the perfect participle *libratum* as either fall or level. Instead of *libratum*, certain codices read *libramentum* again (Callebat 1973: 28). Rowland's (Rowland, Howe *et al.* 1999) translation of the relevant parts of passage 8.6.5 reads: "If the source has a **downward incline** toward the city walls, […] When the watercourse reaches the valley bottom, it should not be elevated high on masonry substructures; **the fall** should be as long and as gradual as possible." In contrast, Morgan (1960) interprets *libratum* as level: "If there is a **regular fall** from the source to the city, […] On reaching the bottom, a low substructure is built so that the **level** there may continue as long as possible." He translates the same term with two very different words, indicating a slope in the first instance, and a horizontal level in the second. Similarly, Granger's (1983) text reads: "If from the fountain head there is a **fall** to the city, […] and when it reaches the bottom, it is carried on a low substructure so that it may be **leveled** as far as possible." Likewise Callebat (1973): "si l'on a une **pente** constante depuis la source jusqu'aux murs de la ville, […] Quand la canalisation arrive au point le plus bas, on élève une assise de faible hauteur pour que le plan soit maintenu le plus longuement possible de **niveau**.” Grimal (1945: 163-4) interprets *libramentum* and *libratum* as “level” throughout, suggesting: “Si **le niveau** de la source est maintenu jusqu’à la ville, […] une fois le bas atteint, on établira des substructions de faible hauteur, pour que la partie **nivelée** soit aussi longue que possible.” The term *libramentum* occurs 18 times in all of *De architectura* (Callebat, Bouet *et al.* 1984). In cases that are not related to water supply, the term clearly denotes a horizontal level. In *De architectura* 8.6.1, the only case where Vitruvius writes without a doubt about a slope or gradient of a water course, he mentions *libramenta fastigata*, “sloping levels”: *si canalibus, ut structura fiat quam solidissima, solumque rivi libramenta habeat fastigata ne minus in centenos pedes sicilico*. “For channels, the masonry should be as solid as possible, and the floor of the watercourse should have a slope calculated to be no less than half a foot every hundred feet” (Rowland, Howe *et al.* 1999). The necessity to modify the noun *libramenta* with the attribute *fastigata* to express the meaning of slope indicates that words related to *libramentum* without further modification denote a horizontal situation.

In *De architectura* 8.6.5 it is important to note that the technique that Vitruvius is suggesting can be applied in a situation where source and city are on the same level with an intervening depression. A pipeline does not require a slope to work. Merely a water-filled basin on the header side with a pipe leading out from its bottom is necessary for the water to flow, even if the pipe is horizontal (Fig. 2.1a, b, c). The “horizontal” stretch of pipeline in the Gier aqueduct at Lyon even slopes upward by *ca.* 1% (Burdy 2002b: 245).

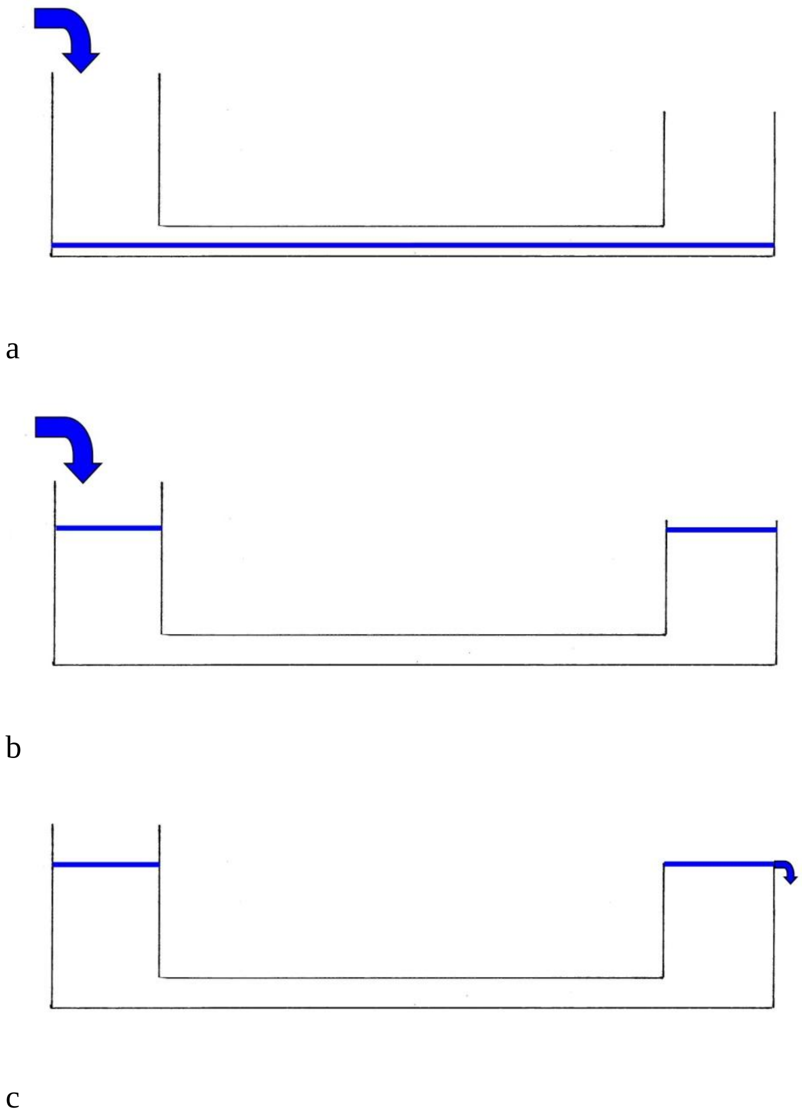

Figure 2.1a, b, c: Water Flowing Through a Horizontal Pipeline

In an inverted siphon the water rises back to nearly its own level through the U-shaped structure. The slight loss in elevation due to the establishment of a hydraulic gradient is negligible in comparison with the depth that an inverted siphon can reach. Therefore, it is perhaps more justified to translate *libramentum* as “level” than “slope”.

Lexicon entries for *libramentum* in the *Oxford Latin Dictionary* (*OLD*) and in Lewis and Short require new consideration. In the *OLD*, entry 3b for *libramentum* reads:

> **3b** the inclined plane of a watercourse, gradient.
>
> ut… solum… rivi ~a habeat fastigata ne minus in centenos pedes sicilico VITR. 8.6.1; ut sit ~um quam longissimum 8.6.5; praeceps esse ~um opportet, ut ruat uerius quam fluat Plin. *NH* 33.74; Fron. *Aq*.6.

The first entry is the only passage related to water in *De architectura* where *libramentum* means gradient, because the noun is modified by the attribute *fastigatum*. *Libramentum* by itself, without a modifying adjective, seems, therefore, insufficient to denote a gradient. In the second entry *libramentum* means horizontal, by overwhelming agreement of all translators of the passage, except Rowland (Rowland, Howe *et al.* 1999). In the third entry Pliny does not mean gradient but rather a motive power that approximates our modern notion of impulse or momentum in the sense of the Latin *impetus*. The primary meaning for *libramentum* in the *OLD* is indeed "a weight used to operate a mechanism", and Lewis and Short write: "a weight for giving motive power". Pliny the Elder uses *libramentum* in just the sense of "momentum" in *NH* 31.31:

> "*[aqua] subit altitudinem exortus sui. si longiore tractu veniet, subeat crebro descendatque, ne libramenta pereant*."

> “Water rises as high as its source. If it comes from a long distance, the pipe should frequently go up and down, so that no momentum may be lost.” (trans. W.H.S. Jones, LCL)

Jones translates *libramentum* as momentum, which seems correct. Pliny apparently had a misconception about the possibility of adding energy to flowing water by repeatedly elevating the pipeline. He thought that by bringing the pipe back up to a certain level and letting it descend again, energy would be added to the system, and thus the “force of flow” be rewound like a mechanical clock.

In the passage from Fron. *Aq.* 6, *libramentum* can also mean “level”.

> *concipitur Anio vetus supra Tibur <via Valeria> vicesimo miliario extra portam [. .]RR^[. .]nam, ubi partem dat] in Tiburtim usum. ductus eius habet longitudinem, ita exigente libramento, passuum quadraginta trium milium.* (Fron. *Aq*. 6)

> The intake of Old Anio is above Tibur at the twentieth milestone outside the … Gate, where it gives a part of its water to supply the Tiburtines. Owing to the exigence of elevation, its conduit has a length of 43,000 paces. (trans. C. E. Bennett, LCL)

In the Loeb edition, Bennett translates *libramentum* as “elevation”, *i.e.* as a horizontal level; not as gradient or slope. According to Rodgers (2004: 156), “Frontinus explains that the length of the conduit is a consequence of its *libramentum* ‘gradient’, the result of the process of leveling.” But it is as correct to state that the length of a conduit is a consequence of the *libramentum* ‘level’ of its intake, namely above Tibur.

Lewis and Short list different passages under the entry for *libramentum*:

> **B.** *A fall, descent* of water: libramentum aquae, Plin. 31, 6, 31, § 57: quod libramentum cum exinanitum est, suscitat et elicit fontem, cum repletum, moratur et strangulat, of a spring that alternately rises and falls, Plin. *Ep*. 4, 30, 10: inferiore labro demisso ad libramentum modicae aquae receptae in fauces, palpitante ibi lingua ululatus elicitur, of the croaking of frogs, Plin. 11, 37, 65, § 173.

Only in the first instance does *libramentum* mean the gradient of a water conduit, as Pliny gives its slope as a quarter of an inch to 100 feet: “libramentum aquae in centenos pedes sicilici minimum erit…” The gradient of the water should be at least a quarter of an inch every hundred feet (trans. Jones, LCL). Pliny does not expressly mention Vitruvius in his list of sources. But the close similarity between this passage and *De architectura* 8.6.1 (“rivi libramenta habeat fastigata ne minus in centenos pedes sicilico”) may indicate that Pliny possibly copied the information in perhaps a rather negligent manner from Vitruvius, so that the modifying adjective *fastigata* fell by the wayside.

In the second entry, from Pliny the Younger, *Ep*. 4, *libramentum* again denotes a motive power or kinetic energy that controls the spring in question. It should certainly not be translated as descent or fall. Radice’s (LCL) translation reads: “Or is there some force of water hidden out of sight which sets the spring in motion when it has drained away, but checks and cuts off the flow when it has filled up?” The English translation of the word *libramentum* as “force of water” is quite different from “slope” or “gradient”.

In the third entry, from Pliny the Elder, it is quite clear that the water is taken up by the frog up to the level of the lowered lip. Rackham’s translation from the Loeb edition reads: “In this process they just drop the lower lip and take into the throat a moderate amount of water and let the tongue vibrate in it so as to make it undulate, and a croaking sound is forced out.” Again, the English translation employs no equivalent word for *libramentum*, again, because “gradient” or “slope”—the common translation in relation to water—do not fit the context. It follows that *libramentum* has too readily been translated as “gradient” when “level” would have been correct. The difference between the two meanings is sufficient to obscure nuances in the original texts and cause uncertainty about the translation of passages where *libramentum* cannot mean “gradient”.

The term *venter* has been generally used only for the level portion of a pipeline crossing the valley bottom. Kessener (2001: 148) and Lewis (2001: 349) suggest that the entire U-shaped portion of pipeline constitutes the *venter*. Hence, the structure that we call “inverted siphon” must be understood as *venter*. Both *venter* and *koilia* in Greek are used to describe either concave or convex forms, or bulging or sagging things. *Koilia*, moreover, means “intestines” or “bowels”, also indicating that Vitruvius uses the term probably for the entire pipeline (Glare 1982; Liddell and Scott 1996). Therefore, using it for a straight structure would be inconsistent.

The term *geniculus* also deserves a second look:

> 6 Quodsi non venter in vallibus factus fuerit nec substructum ad libram factum, sed *geniculus* erit, erumpet et dissolvet fistularum commissuras. Etiam in ventre colluviaria sunt facienda, per quae vis spiritus relaxetur. Ita per fistulas plumbeas aquam qui ducent, his rationibus bellissime poterunt efficere, quod et decursus et circumductiones et ventres et expressus hac ratione possunt fieri, cum habebunt a capitibus ad moenia ad fastigii libramenta. (*De arch.* 8.6.6)

> 6 If, however, neither a *venter* is built in the low portion nor a substructure to create a level, but the line forms a sharp convex bend instead, the bend will come apart and sever the joints between the pipe segments. Furthermore *colluviaria* through which pressure is released must be added in these places. If water is to be conducted through lead pipes, it will be best accomplished in this way because the descents, the detours, the *ventres*, and ascents can be realized by this method if the header tank and the city are on the same level.

Static pressure, generated by the weight of the water column resting above the locus in question is the critical physical property that a pipe has to withstand. The deeper the dip in the pipeline, the higher the static pressure will be. Forces generated by static pressure at bends in an inverted siphon may push the corner segment out of the line. The forces generated by this pressure exert a tensile stress on the pipe wall, which can be easily controlled by increasing the wall thickness, as was done at Alatri. The problem zones, Vitruvius clearly states, are the joints between the pipes, *commissuras*. The static pressure generates two axial force vectors whose resulting force threatens to push the corner segment out of line and burst the joints. In previous interpretations these bends in the pipeline were thought to be concave (de Montauzan 1909: 185; Hodge 1992: 151; Burdy 2002b: 244) (Fig. 2.2).

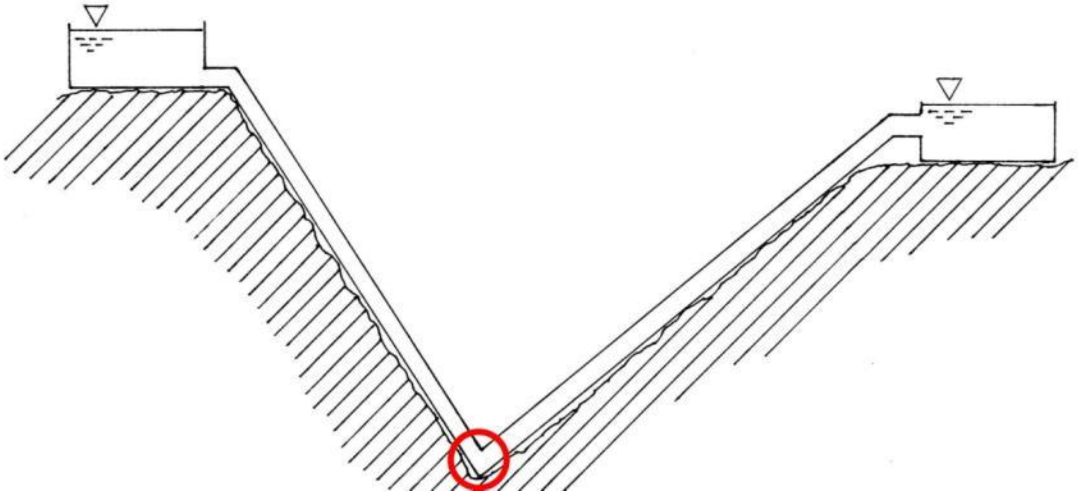

Figure 2.2: Geniculus?

If the *geniculus* is concave, however, this force is checked by the foundation (Fig. 2.3). It is, therefore, more plausible that the *geniculus* in this passage is convex.

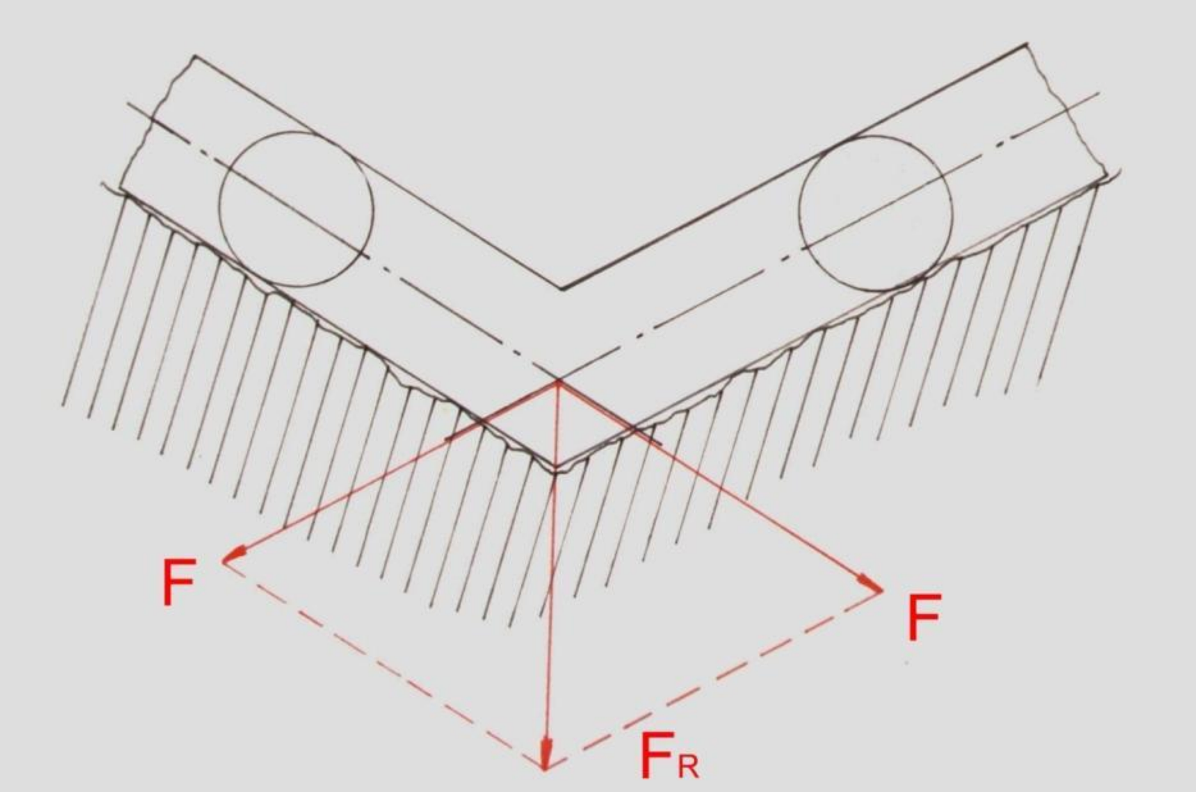

Figure 2.3: Concave Bend – Forces Checked by Foundation

A problem arises in horizontal and convex vertical bends. In such a case the pipe is relatively free to move sideways or upward, and the structural integrity of the line is at risk (Fig. 2.4). A heavy block or anchor located at the outside of the bend must check the forces acting sideways or upwards. Such blocks on the summits of the intermediate hills ("Gipfelsteine") anchored the pipeline of the inverted siphon at Pergamum (Garbrecht 1978: Figs. 7-8). Since Vitruvius wrote in the first century B.C., it is evident that he had the Hellenistic pipelines, such as those at Pergamum and Smyrna in mind and not the later Imperial Roman systems, such as those at Aspendos and Yzeron.

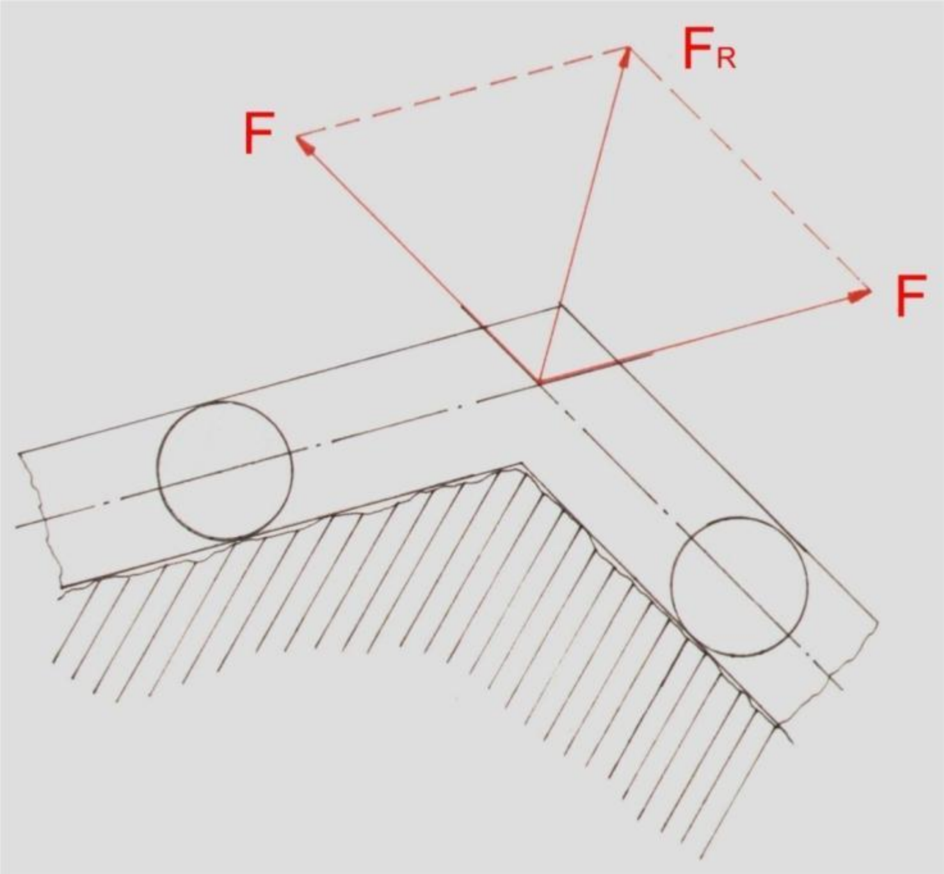

Figure 2.4: Convex Bend - Forces Unchecked

A hollow cylinder under high pressure is in danger of bursting lengthwise rather than around the circumference. Kessener (2001: 141) compares the situation to a sausage in a frying pan. He reasons, therefore, that a lead pipe is unlikely to burst at the joint between adjacent segments. But since the inverted siphons at Alatri and Pergamum consisted of cast lead pipes, the engineers were able to adapt the wall thickness of the pipes to the high pressures with a sufficient safety margin. Belgrand's often quoted experiment (de Montauzan 1909: 202; Hodge 1992: 311), in which he subjected lead pipes made of bent and soldered sheets—the type predominant in the archaeological record—to high pressures further contributes to the confusion, as such pipes were not utilized in large-scale inverted siphons, but merely in those of smaller size, such as that at Arles or those in urban distribution systems (Hodge 1992: 312). In pipelines made of cast segments, however, the joints between pipe segments would have been weak points in comparison to the massive, seamless pipe shafts. The pipe segments usually slid into each other and were held together by the force of the solder and a nail that penetrated both pipes at the joint overlap (Kessener 2001: 141). In a straight section of the pipeline, where no displacement is possible, this locking method would have been sufficient to maintain the integrity of the line. At a bend, however, water at high pressure would have pulled apart such joints if they were unsupported by other means. Therefore, at Pergamum the designers used stone blocks on the intervening hills to hold the pipeline in place and prevent the joints from bursting (Stehlin 1918: 170; Fahlbusch and Peleg 1992: 123).

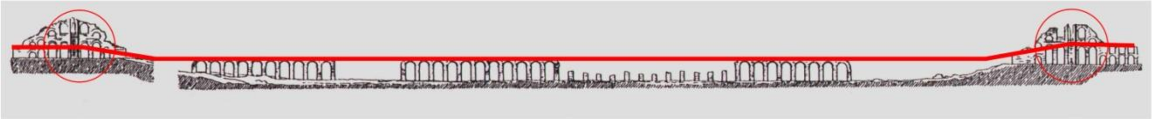

Figure 2.5: Two convex *geniculi* (circles) would appear in the course of the inverted siphon at Aspendos if the towers were absent.

Pipelines made of stone segments were also vulnerable to these forces. The towers in Aspendos are located at horizontal bends in the pipeline. In the absence of the towers, the line would have bent not only sideways, but also vertically in two convex bends (Fig. 2.5). The resulting force would have been directed upwards at an angle with a potential of lifting the corner segments out of the pipeline. The structural integrity of a stone pipeline with mortared plug-and-socket joints between the individual segments is not as high as that of a lead pipeline with soldered joints. With multiple joints only 50 cm apart, there was danger of pipe rupture in many places. Hodge (1983: 189) suggested, therefore, that the pressure at the bends with problematic geometry was relieved by raising the water to the level of the hydraulic gradient. The towers were a technologically awkward but safe solution. Moreover, prestige and aesthetics may have made this configuration attractive.

Local high points in the pipeline constitute convex bends. Air blocks can occur downstream from these high points. Valves or vents are required to release the entrapped air, perhaps Vitruvius' *vis spiritus*? It is noteworthy in this context that Schnappauf (1966: 371) calls the expansion and contraction of the air block due to changes in water flow velocity "Atmen", breathing in English or *spiritus* in Latin. Vitruvius may have thought of such valves when he wrote about *colluviaria*. A possible example of a *colluviarium* is the tower in the inverted siphon at Yzeron, built to drain an air block that formed during the initial filling of the inverted siphon (Kessener 2000a: 130).

It is a daunting task to attempt a summary of all the writing that has been published in reference to *colluviaria*, even though the word occurs nowhere else in Latin literature. Mortet (1907: 77) and de Montauzan (1909: 187-90) mention four alternative spellings in various editions, *colliviaria* (MSS), *colluviaria* (MSS), *columnaria* (Rode 1796), and *columbaria* (Laët 1649). Fahlbusch and Peleg (1992: 109), in addition, list the spellings *calluviaria* (Prestel 1912) and *colleniaria* (Choisy 1909). Fensterbusch (1964) suggests *colliquiaria*, which, "through the root *LIQ*, is at least connected with liquid" (*i.e. liquo*) (Hodge 1983: 214). Rowland (Rowland, Howe *et al.* 1999: 105) suggests the emendation *collaxaria*.

The following selection of emendations and translations shows the difficulty of a proper understanding:

Prestel (1913, German) *calluviaria*	Spülbecken (“flushing basin”)
Fensterbusch (1964, German) *colliquiaria*	Kolliquiarien
Kottmann (1984, German) *?*	Entlüftungen (air vents)
Choisy (1909, French) *colleniaria*	adoucis (softener?)
Callebat (1973, French) *colliuiaria*	*colliuiaria*
Granger (1931, English) *colluviaria*	stand-pipes
Morgan (1970, English) *colliviaria*	water-cushions
Humphrey, Oleson, and Sherwood (1998, English) *colluviaria*	vents, lit. “clean-out taps”
Rowland (1999, English) *collaxaria*	dilations

For the French scholars of the early twentieth century there was no doubt that the two spellings *colliviaria* and *colluviaria* must be derived from *colluvies* (“washings”, “dregs”), and mean, therefore, a drain pipe at the lowest point of the inverted siphon, probably fitted with a tap, to allow accumulated sediments to leave the pipeline or to allow a complete draining of the pipeline for maintenance (Mortet 1907: 80-1; de Montauzan 1909: 187), a view that is shared by Hodge (1983: 216). Problematic in this context is the missing material evidence. Taps found in the urban distribution system of Pompeii were apparently able to withstand pressures of only some 6-8 m of water column, *i.e.* the height of the secondary water towers in the city. Whether these or similar taps would have been able to manage pressures of close to 200 m of water column, such as at Pergamum, or even only some 40 m, such as at Aspendos is unknown, though it is unlikely. De Montauzan suggests, moreover, that these drain pipes were left open during the filling of the pipeline to decelerate the filling process and allow air to escape ("*ut vis spiritus relaxetur*"), as well as to prevent water hammer ("coups de bélier"), which he suggests would have resulted from uncontrolled filling of the pipeline (de Montauzan 1909: 188). De Montauzan rejects the alternative readings of *columnaria* and *columbaria*, commonly interpreted as "valves" in the context of inverted siphons, because such valves would have to be installed at high points in the line, a necessity at odds with the position *in ventre*, prescribed by the Vitruvian text (de Montauzan 1909: 188-9). The word *columnaria* would have to be related to columns, and de Montauzan acknowledges the existence of such structures that serve as closed surge tanks in modern pipelines. Such tanks are connected with the pipeline by a vertical branch-off and lead into a closed chamber containing an air bubble, which a potential pressure surge would compress and so dissipate its energy, though de Montauzan (1909: 189) insists that these are not what Vitruvius meant. In contrast, Bestué Cardiel and Gonzáles Tascón (2006: 312) refer rather carelessly and without further comment to the raised header tank of an inverted siphon at Almuñécar (ancient Sexi) as *columnaria*. The reading *columbaria* is interpreted as open vertical pipes that likewise serve as surge protectors, connected to the main pipeline and built into columns or towers. In view of the different spellings of the word and their unsuccessful discussion in scholarship over decades, Ohlig (2006: 319) suggests quite rightly that a continued discussion on the etymological level makes no sense: "… aber die inzwischen über Jahrzehnte reichende Diskussion über die richtige Lesart und deren Deutung und Bedeutung hat zu keinerlei Einigung und Ergebnis geführt. Auf dieser Ebene weiterzudiskutieren erscheint deshalb wenig sinnvoll."

De Montauzan (1909: 189-90), quoting Delorme and Flachat, mentions towers ("*suterazı*") in the Roman aqueduct at Constantinople, though he denies again that Vitruvius had such installations in mind. One or more towers with embedded vertical pipes are present also at Methymna (Buchholz 1976), in the urban distribution system at Pompeii (Larsen 1982), and, from the mediaeval period, in the German city of Goslar (Flachsbart 1928: 19). Contrary to de Montauzan's opinion, the towers at Aspendos and Yzeron are also likely candidates for *colliviaria* (Fahlbusch 1987: 25). Tölle-Kastenbein (1990: 94) strictly rejects the notion that *colliquiaria* (her preferred spelling) must be equated with the so-called hydraulic towers. Callebat (1973: 172-3), like de Montauzan, rejects *columnaria* and *columbaria* as possible emendations. He denies the existence of 'columns' on aqueducts altogether and thereby ignores the archaeological evidence. Callebat also rejects the emendation *colleniaria*, suggested by Choisy, that would imply a smooth curve within the pipeline (Callebat 1973: 173-4).

The reading *colliquiaria* is interesting because of its possible echo in Pliny the Elder (*NH* 31, 58), which reads: "*in anfractu omni colliquiaria fieri, ubi dometur impetus necessarium est*," (At every bend, where it is necessary to control the momentum, *colliquiaria* must be built,) though this passage, too, has a variant reading in a number of manuscripts: "*in anfractu omni colli(s) quinaria fieri*" (at the bend of every hill a five-finger pipe must be installed.) A scribal error in this context is quite possible. The first variant is attractive because the passage deals with inverted siphons and would thus repeat the untranslatable *colliquiaria* from Vitruvius in the same context. Pliny's text does not, however, contribute to a better understanding of the term. The second variant is as likely as the first—and accepted by Jones without even a footnote in the Loeb edition—, since the word *quinaria* (“five-finger pipe”, representing the circumference of a lead pipe) occurs twice before in the same paragraph. The *lectio quinaria* allows an interpretation of a bundle of smaller pipes that replace a larger pipe at some bend on or at a hill (“*in anfractu collis*”) where rather big forces may be expected to occur (Callebat 1973: 174). Nothing in the Plinian passage confirms, according to Callebat, that the devices recommended by Vitruvius serve to vent air bubbles. Since Vitruvius suggests the installation of *colliviaria*—Callebat’s preferred spelling—at the bottom of the siphon, Callebat (1973: 175) suggests, like de Montauzan, that they are drainage pipes through which the inverted siphon was evacuated, and that may have remained open in the filling process to prevent pressure surges. Hence, his French translation reads “purgeurs” (perhaps “purge valves”). Hodge (1983) follows this interpretation and likewise interprets *colliviaria* as drain cocks.

According to Fahlbusch and Peleg (1992: 110), Vitruvius’ description of the purpose of these installations clearly states that they avoided or reduced a pressure or destructive force of some sort (“*vis spiritus relaxetur*”). They ascribe the force unequivocally to air (*spiritus*). Hence, they argue, drain cocks are out of the question, since those would not reduce any force that could be described as *vis spiritus* (Fahlbusch and Peleg 1992: 111). Ohlig (2006: 319-20) suggests that the term *vis spiritus* has been translated all too readily as “air pressure”, since the Latin term for “air” as an element in the Empedoclean sense is *aer*, not *spiritus*. He argues at length that *spiritus* in the context of the Vitruvian passage cannot mean air, but must be synonymous with *intentio*, "tension" or "pressure", as a motive force responsible for setting water in motion. Seneca uses *spiritus* in just that sense in *QN* 2.9.2-3 where he describes the force that propels water from a decorative fountain. The discussion of the passage ought to include the broader context of *QN* 2.8-10. The following passages, including the translation, are excerpts from the LCL-edition, edited and translated by Corcoran. I have substituted the original Latin word *spiritus* wherever the translator has chosen to render it as "air".

> 2.8.1 Nunc autem esse quamdam in rerum natura uehementiam magni impetus est colligendum. Nihil enim non intentione uehementius est, tam mehercule quam nihil intendi ab alio poterit, nisi aliquid per semet fuerit intentum, - dicimus enim eodem modo non posse quicquam ab alio moueri, nisi aliquid fuerit mobile ex semet; - quid autem est quod magis credatur ex se ipso habere intentionem quam spiritus? Hunc intendi quis negabit, cum uiderit iactari terram cum montibus, tecta murosque, magnas cum populis urbes, cum totis maria litoribus?
>
> 2.9.1 Ostendit intentionem spiritus uelocitas eius et diductio. Oculi statim per multa milia aciem suam mittunt; uox una totas urbes simul percutit; lumen non paulatim prorepit sed semel uniuersis rebus infunditur.
>
> 2.9.2 Aqua autem quemadmodum sine spiritu posset intendi? Numquid dubitas quin sparsio illa quae ex fundamentis mediae harenae crescens in summam usque amphitheatri altitudinem peruenit cum intentione aquae flat? Atqui nec manus nec ullum aliud tormentum aquam potest mittere aut agere quam spiritus; huic se

commodat; hoc attollitur inserto et cogente; contra naturam suam multa conatur et ascendit, nata defluere.

2.9.3 Quid? Nauigia sarcina depressa parum ostendunt non aquam sibi resistere, quo minus mergantur, sed <u>spiritum</u>? Aqua enim cederet nec posset pondera sustinere, nisi ipsa sustineretur. Discus ex loco superiore in piscinam missus non descendit, sed resilit; quemadmodum, nisi <u>spiritu</u> referiente?

2.9.4 Vox autem qua ratione per parietum munimenta transmittitur, nisi quod solido quoque aer inest, qui sonum extrinsecus missum et accipit et remittit, scilicet <u>spiritu</u> non aperta tantum intendens, sed etiam abdita et inclusa, quod illi facere expeditum est, quia nusquam diuisus est sed per illa ipsa quibus separari uidetur coit secum? Interponas licet muros et mediam altitudinem montium, per omnia ista prohibetur nobis esse peruius, non sibi. Id enim intercluditur tantum per quod illum nos sequi possumus. Ipse quidem per ipsum transit quo scinditur, et media non circumfundit tantum et utrimque cingit, sed permeat.

2.10.1 Ab aethere lucidissimo aer in terram usque diffusus est, aggilior quidem tenuiorque et altior terris nec minus aquis, ceterum aethere spissior grauiorque, frigidus per se et obscurus. Lumen illi calorque aliunde sunt.

2.10.2 Sed non per omne spatium sui similis est; mutatur a proximis. Summa pars eius siccissima calidissimaque et ob hoc etiam tenuissima est propter uiciniam aeternorum ignium et illos tot motus siderum assiduumque caeli circumactum; illa pars ima et uicina terris densa et caliginosa est, quia terrenas exhalationes

> receptat; media pars temperatior, si summis imisque conferas, quantum ad siccitatem tenuitatemque pertinet, ceterum utraque parte frigidior.
>
> 2.10.3 Nam superiora eius calorem uicinorum siderum sentiunt. Inferiora quoque tepent; primum terrarum halitu, qui multum secum calidi affert ; deinde quia radii solis replicantur et, quousque redire potuerunt, id duplicato calore benignius fouent; deinde etiam illo <u>spiritu</u> qui omnibus animalibus arbustisque ac satis calidus est, nihil enim uiueret sine calore. (Sen. *QN* 2.8.1-2.10.4)

> 2.8.1 It requires no lengthy thought that in nature certain things exist which have violent movement and enormous force; yet nothing becomes more violent but by tension; and equally, by Hercules, nothing can be in tension from another object unless it has tension itself. In the same way we say that nothing can be moved by another object unless there is the capacity of mobility in it. But what is more likely to have tension within itself than *spiritus*? Who will say that *spiritus* does not have tension when he sees it toss about lands and mountains, houses and walls, great cities and their peoples, seas with their entire coastlines? (trans. adapted from T. H. Corcoran, LCL, who translates *spiritus* as “air”)

I believe it is misleading to translate *spiritus* as air in this context because Seneca clearly describes the effects of earthquakes and volcanic eruptions (*iactari terram cum montibus, tecta murosque, magnas cum populis urbes, cum totis maria litoribus*). Granted, *spiritus* can also mean wind. In fact Seneca himself gives that definition:

> spiritum a vento modus separat: vehementior enim spiritus ventus est, invicem spiritus leviter fluens aër. (Sen. *QN* 5.13.4)

> The degree of movement separates *spiritus* from wind; for the more violently moving *spiritus* is wind. On the other hand, gently flowing *spiritus* [Corcoran: "atmosphere"] is air. (trans. adapted from T. H. Corcoran, LCL)

Storms can be violent. The image of tossing earth and mountains, though, and shifting coastlines, *i.e.* the change of topographical features indicates a tectonic event, caused by tension in the earth's surface rather than by a storm. A translation of *spiritus* as "air", therefore, is incorrect in this passage.

> 2.9.1 The velocity and expansion of *spiritus* shows its tension: the eyes send their sight instantly over many miles, a single sound at one moment resounds through entire cities, light does not creep forth gradually but in an instant pours over all things.

> 2.9.2 Moreover, how could water be in tension without *spiritus*? Take the jet of water that grows from the bottom of the centre of the arena and goes all the way to the top of the amphitheater—do you think this happens without tension of the water [Corcoran: "air tension"]? Yet neither the hand nor any sort of mechanical device can emit or force water out the way *spiritus* can. The water responds to the *spiritus*. It is raised up by the *spiritus*, which is inserted in the pipe and forces it

> up. Although water naturally flows down, it struggles mightily against its nature and rises.
>
> 2.9.3 How about ships laden with cargo? Do they not show that it is the resistance of *spiritus,* not of water, that keeps them from sinking? Water would give way and be unable to maintain the weight if it were not itself sustained by *spiritus*. A discus hurled from a higher position into a pond does not sink but bounces back. How could it do this unless it was beaten back by *spiritus*?
>
> 2.9.4 How is a voice transmitted through the barrier of a wall unless air [*aer*] exists in the solid matter also? Air [*aer*] receives the sound sent from outside and passes it on. The energy of *spiritus* exerts tension not only on exposed matter but also on concealed and enclosed matter. *Spiritus* can do this easily because it is never divided but maintains continuity with itself even through objects which seem to separate it. Although you interpose walls and obstructing high mountains, through all such barriers a passageway is prevented not for itself but only for us. For, the only block is that through which we are not able to follow *spiritus*; but *spiritus* passes through the very obstacle which separates it. It not only pours around and encircles obstacles in its midst but even permeates them. (trans. adapted from T. H. Corcoran, LCL)

In this passage, too, *spiritus* does not mean air. The jet of water in passage 2.9.2 is propelled upward not through air but through static pressure—a physical property that was unknown to Seneca, but whose motive effect cannot be mistaken for air. *Spiritus* must mean “motive or animating force” or “tension”. Even more striking is the example of the floating ship (*QN* 2.9.3). It is very unlikely that Seneca believed a ship to float on water because air, in turn, supports the water. He writes that “water would give way” to the weight of the ship. How much more true would this statement have to be for air, many times less dense than water? Again, *spiritus* must mean something akin to “tension”; and, indeed, it is the surface tension of the water that keeps water striders afloat. The bouncing of the discus over the water surface, too, is a result of the higher density of water and the angle of impact on the water surface.

The example of sound propagation (2.9.4), too, demonstrates that a translation of *spiritus* as air is insufficient to capture the full meaning of the text. For one, where Seneca means air, he uses the Latin word *aer* (*cf.* also *QN* 2.10.1-3 below). He reserves *spiritus*, therefore, for conveying a special meaning. In the case of acoustic wave propagation I suggest as a better translation the word “elasticity”; a physical property closely related to tension, or, more properly, to stress in the physical sense. *Spiritus* is not a material element or a medium, but rather a physical property that the medium has. The medium can be air, but it can also be water, as the above examples show.

> 2.10.1 Air [*aer*] is diffused from the bright atmosphere down to earth. It is thinner more mobile, and more buoyant than earth and water too but thicker and heavier than upper atmosphere. By itself air [*aer*] is cold and dark. Its light and heat are from another source.

> 2.10.2 Air [*aer*] is not the same throughout its entire expanse. It is altered by its surroundings. Its highest region is extremely dry and hot, and for this reason also

> very thin because of the nearness of the eternal fires, the many movements of the stars, and the continuous revolution of heaven. The lowest region, near the earth, is dense and dark because it receives the terrestrial exhalations. The middle region is more temperate (compared to the highest and lowest regions, as far as dryness and thinness goes), but it is colder than both the other regions.
>
> 2.10.3 The upper regions of air feel the heat of the nearby stars. The lower regions are also warm; first because of the exhalation of the earth, which carries with it a great deal of warmth; second, because the rays of the sun are reflected back and make the air more genially warm with reflected heat as far as they are able to reach. Besides, the lower air is warmed by the breath [*spiritus*] which comes from all the animals, trees, and plants; for nothing is alive without heat. (trans. adapted from T. H. Corcoran, LCL)

This passage shows that *aer* is different from *spiritus.* Where Seneca means the element “air”, he invariably uses the word *aer. Spiritus* is clearly related to the quality of being alive that is inherent to animals, trees, and plants. These living beings are warmed by *spiritus*, because without the warmth of *spiritus* nothing is alive.

In *QN* 6.1-32 Seneca describes the origin of earthquakes and the effect of *spiritus* in that context. The passage is too long to be considered in detail in this thesis. *Spiritus* occurs 55 times in book 6 of *QN.* In both the LCL edition and in the German Reclam edition the word has been translated in most these instances as “air” or “Luft”, German for air. I wish to argue that here, too, such a translation is not sufficiently precise. Two representative examples will prove my point.

> Quidam ignibus quidem assignant hunc tremorem, sed aliter. Nam cum pluribus locis ferueant, necesse est ingentem uaporem sine exitu uoluant, qui ui sua spiritum intendit et, si acrius institit, opposita diffindit, si uero remissior fuit, nihil amplius quam mouet. (Sen. *QN* 6.11.1)

> Some, indeed, attribute earthquakes to fire but give different explanations. When heat grows intense in many places it necessarily rolls up an enormous cloud of vapour that has no way out and causes strain on the *spiritus* by its force. If the vapour exerts excessive pressure it breaks through all that opposes it; but if it is fairly moderate it causes nothing more than a movement of the earth. (trans. adapted from T. H. Corcoran, LCL, who translates *spiritus* as "air")

The *spiritus* in this passage is unlikely to mean "air". The preceding text mentions nowhere the presence of air in the cavities that are subsequently filled by vapor. The passage rather explains how the expanded vapor increases tension. *Spiritum intendit* is, to my mind, a pleonasm that expresses the "tensing of tension".

The following passage likewise proves my argument:

> Spiritum esse qui moueat et plurimis et maximis auctoribus placet. Archelaus, uir quidem satis diligens, ait ita: Uenti in concaua terrarum deferuntur; deinde, ubi

> iam omnia spatia plena sunt et in quantum aer potuit densatus est, is qui superuertit spiritus priorem premit et elidit ac frequentibus plagis primo cogit, deinde proturbat; (Sen. *QN* 6.12.1)

> It is a favourite theory of most of the greatest authorities that it is *spiritus* which causes earthquakes. Archelaus, a scholar accurate in matters of ancient times, says as follows: winds [*venti*] are carried down into cavities of the earth; then, when all the spaces are filled and the air [*aer*] is thickened as much as it can be, *spiritus* which comes in on top of it compresses the *spiritus* that was there first and pushes it and with frequent blows first packs it together then forces it out. (trans. adapted from T. H. Corcoran, LCL)

Once again there is a clear distinction between *aer* as a material medium and *spiritus* as a physical property. Here, *spiritus* means pressure or tension. Pressure from above increases the pressure of the air in the underground cavity.

Vis spiritus, therefore, ought not to be translated as air pressure, an observation proposed already by Stehlin (1918: 171), but should mean “motive, vital, or cohesive force”. I suggest the literal translation “force of the compression”. Ohlig (2006: 324) concludes that *colliviaria* cannot be devices for the removal of air from water pipelines, but their function is to reduce, dampen, or relax (*relaxetur*) a surplus of a force that Vitruvius calls *vis spiritus*. Hodge (1983: 210; 1992: 154) and Smith (1976: 57) both insist that Vitruvius *must* mean air pressure, only to state immediately that there *was* no air in an inverted siphon, and that, therefore, Vitruvius *must* have been wrong. Kessener

(2002b: 197), too, reads *vis spiritus* as air pressure and suggests quite rightly that air slugs could very well occur in inverted siphons. His convoluted conclusion is, therefore, that *colliquiaria* (his preferred spelling) must have been “air vents in the form of a lead pipe (*quinaria*) soldered on top of the conduit at the start and at the end of an inverted siphon incorporated in an aqueduct system made of lead pipes” (Kessener 2001: 154). There is a great temptation to reconcile the ancient text with the physical phenomenon, but we must be cautious with an interpretation. An inverted siphon is susceptible to problems associated with the presence of air bubbles, but this is not what Vitruvius is concerned with in this passage when he warns of the *vis spiritus*.

Since Vitruvius used Greek sources, a look at πνεῦμα–the Greek equivalent of *spiritus*–is instructive (Lewis 2000: 349). As the above passages by Seneca illustrate, the Stoic idea of πνεῦμα is that of an active principle that interpenetrates all matter, lifeless by nature, and endows living things with their characteristic properties, an idea introduced by the Stoic Athenaeus. He introduced πνεῦμα as the fifth element (Harris 1973: 238). Πνεῦμα is a “source of vitality and rationality in the cosmos. […] *Pneuma* exists in a state of tension or elasticity. This tension accounts for that most basic property of all objects, cohesion. At higher levels, different tensions account for the variety of properties and personalities observable in the world” (Lindberg 1992: 81-2). Hence a translation of *spiritus* as merely “air pressure” may fall short of the meaning that the word or its Greek equivalent πνεῦμα had in antiquity, though Hero in *Pneum.* 1 states: οὐδὲν γὰρ ἕτερός ἐστι τὸ πνεῦμα ἣ κινούμενος ἀήρ. “For *pneuma* is nothing other than moving air.” In Greek medicine, Erasistratus (Fourth century B.C.), quoted by Galen *Nat. Fac.* 2.6.97, examined the pumping action of the heart and explained that arterial blood transported πνεῦμα to all parts of the body (Lindberg 1992: 121). Interesting in this context is that the Greeks called the left ventricle of the heart κοιλία, the same word they used, according to Vitruvius, for the *venter* of an inverted siphon. A search in the TLG reveals that the words βία and πνεῦμα, Greek equivalents of *vis* and *spiritus*, occur in close proximity numerous times in texts by Galen in the context of blood that is pumped through the arteries. The parallel of blood flow in an artery with water flowing in a pipeline under pressure is obvious. The comparison suggests the question whether Vitruvius was more specifically thinking of oscillations in the water column during the filling process, inviting an even closer analogy with the cardio-vascular system. Ortloff and Kassinos (2003) demonstrated that such oscillations did indeed occur in the inverted siphon at Aspendos and were influenced by the two towers. I treat this aspect in detail in chapter 3.1. The description of those of Hero's *automata*, in which a liquid is set in motion by means of compressed air, uses specifically the word ἀήρ (*e.g. Pneum.* 1.10). This choice of terminology shows that at least πνεῦμα is not synonymous with air, even when it is under pressure.

Comparing *De architectura* 8.6.6 with *NH* 31.58, discussed above, Pliny the Elder states the necessity to reduce the *impetus*, *i.e.* perhaps some sort of impulse, such as that of a jet of water hitting a wall—not air pressure (Fahlbusch and Peleg 1992: 112). Hydraulic towers, such as those at Lyon or Aspendos, whether intentionally or not, certainly do reduce forces—both those caused by static pressure and those caused by a change in momentum (Stehlin 1918: 171). Furthermore, the tower at Lyon serves to vent an air bubble that would have formed downstream of the high point formed by the intermediate hill. The terracotta pipelines at Caesarea had installations that approximate vertical pipes or “stand-pipes”, as Granger’s (LCL) translation of *colluviaria* suggests (Fahlbusch and Peleg 1992: 113).

The triple-pipeline at Caesarea with pipes of *ca.* 19 cm internal diameter was installed in an originally Hadrianic aqueduct. The pipes were embedded in the mortar at the bottom of what was originally an open channel, suggesting that the line must have been pressurized. The stretch of aqueduct that contained these pipelines was horizontal and had a length of *ca.* 2 km. The inflow was located at an elevation of 15 m a.s.l., the outflow at 11 m a.s.l., and the horizontal stretch at *ca.* 8.85 m a.s.l. The maximum drop in the pipeline was, therefore, 6.35 m (Fahlbusch and Peleg 1992: 114), with a resulting maximum pressure of 0.62 bar. Two installations were built into the aqueduct at a distance of 97 m from each other. They each consist of three 90°-elbows fixed in a mortar bed that brought the water vertically up and immediately down again. The water must have decanted into a basin that is no longer extant. Fahlbusch and Peleg (1992: 114) state that the open basins served to purge air from the pipeline and to dampen possible pressure surges. This interpretation does not explain, however, why these two installations were located at a distance of 97 m from each other in a pipeline that was *ca.* 2 km long. The authors state that the aqueduct survives only in stretches, and that in the 1950s at least one more such installation must have been visible in the line. A second, Byzantine single terracotta pipeline (2.5 km long; internal diameter *ca.* 18-22 cm) south of Caesarea that was discovered and obliterated during the construction of a modern power plant included three very similar installations. One consisted of a rectangular basin (80 x 85 cm), located in a 90°-bend in the line. The bottom of the basin lay only 80 cm above the centerline of the horizontal pipe. The other two installations were damaged, but the remains of one of the two indicate that instead of a basin, the upward and downward pipes were connected by a trough (85 cm long, 20 cm wide, 30 cm deep). The edge of the trough was located 1.1 m above the centerline of the horizontal pipe. Fahlbusch and Peleg (1992: 116; Peleg 1999: 363; 2002: 221) believe that these installations were *colliviaria*. Stone pipe fragments from Smyrna (Weber 1900a) and from Oinoanda (Stenton and Coulton 1986) with 90º-elbows or T-joints indicate, according to Fahlbusch and Peleg (1992: 116), that such vertical pipes may have been rather common in ancient pipelines.

Towers that served as secondary *castella* in urban distribution systems, such as have survived at Pompeii, certainly reduced static pressure and would have alleviated water hammer, pressure surges that would have occurred when domestic taps in the individual households were closed. The 12 extant towers at Pompeii, whose remains now stand 3.0-6.6 m high (Larsen 1982: 51), were fitted with open basins on top, and effectively reduced the maximum pressure at the taps to the value generated by the respective vertical water column resting above the datum line of the tap. The first-order *castellum* at the Porta Vesuviana is located at 42.6 m a.s.l., while the opposite end of the Via Stabiana lies at 8.8 m a.s.l. A direct supply of this part of town from the first-order *castellum* at Porta Vesuvia would have created a water pressure of nearly 34 m of water column (Larsen 1982: 41) or 3.3 bar. A tower of 7 m height reduced the pressure to 0.69 bar. Similar towers are the Ottoman *suterazı* at Constantinople (Andréossy 1828: 385-95; Forchheimer and Strzygowski 1893a: 23-32) and at Akko or Acre (Fahlbusch and Peleg 1992: 118-21), as well as a wooden tower from the 15th century in Goslar in Germany (Flachsbart 1928: 19; Fahlbusch and Peleg 1992: 118-21). These urban water towers with their open basins on top are quite similar to the towers at Aspendos and

Lyon, but the forces that these urban towers helped control were generated by a quite different phenomenon (water hammer) than the forces generated in the long-distance pipelines (change in momentum and static pressure). They also disprove the occasionally surfacing assertion that inverted siphons were little used by the Romans (de Montauzan 1909: 207-8; Hodge 1992: 427, n. 39; De Kleijn 2001: 31), for each of the 12 extant towers at Pompeii represents one inverted siphon between the tower and the primary castellum. The same must have been true for the city of Rome at a much larger scale.

Holes in the walls of a number of Hellenistic pipelines, usually covered with a tight-fitting lid, may also have served as vents for slugs of air (Tölle-Kastenbein 1990: 93). The holes needed to be open only during the filling cycle of the pipeline. Once the air block was drained, the holes had served their purpose and could be sealed permanently. Such holes may have also contained a simple type of air valve, especially if the water supply was so variable that air blocks would have occurred and needed to be removed frequently (Hodge 1983: 204-5; Lewis 1999: 169). Tölle-Kastenbein (1991: 30) and Schwarz (2006: 333) equate these holes with *colliviaria*. Schwarz argues furthermore that the holes were closed with relatively thin lids, so that an air space was created within the pipe walls. These air spaces occurring in intervals may have collected air bubbles that moved downstream with the water, and they may have served as small surge tanks for the dampening of pressure transients (Schwarz 2006: 332).

In essence, it must be said that any attempt to explain what Vitruvius meant by *colliviaria* tries to give meaning to a word of uncertain spelling that occurs only once in all of Latin literature, whose meaning cannot be derived from any other Latin words, that describes an unknown technical installation performing a poorly defined function to solve a number of possible problems: static pressure; change in momentum; water hammer; discharge of air slugs. It is possible that the ancient engineers did not appreciate the differences among these individual problems. They recognized that under certain circumstances strong forces (*vis spiritus*; *impetus*) that were potentially very destructive acted on the pipelines. Therefore, they may have devised some strategies as a panacea without knowing in detail what they did (Fahlbusch and Peleg 1992: 121). Possible extant examples of such installations are rather removed in time from the Vitruvian text. Whether or not features such as "hydraulic towers" or holes in the sides of pipes can necessarily be equated to Vitruvius' *colliviaria* must remain uncertain. "They remain a puzzle" (Hodge 2000b: 83).

Vitruvius' text continues with a recommendation to build *castella* at regular intervals in the pipeline.

> 7 Item inter actus ducentos non est inutile castella collocari, ut, si quando vitium aliqui locus fecerit, non totum omneque opus contundatur et, in quibus locis sit factum, facilis inveniatur; sed ea castella neque in decursu neque in ventris planitia neque in expressionibus neque omnino in vallibus, sed in perpetua aequalitate. (*De arch.* 8.6.7)

> 7 Likewise it is not useless to locate reservoirs at intervals of two hundred *actus*, so that, if ever a place in any way brings forth a defect, the whole work in its entirety does not have to be taken down, and the place where it has occurred is easily found. But these reservoirs can be built neither in a descent, nor in the level

> of the *venter*, nor in elevated sections nor anywhere in the valleys, but only in a completely level stretch.

Fahlbusch suggested that the towers at Aspendos were partition devices subdividing the length of the inverted siphon into smaller portions for maintenance purposes (Fahlbusch 1991). Fahlbusch's interpretation has been dismissed on technical grounds rather than because of its contradiction of Vitruvius (Humphrey 1992).

> 8 Sin autem minore sumptu voluerimus, sic est faciendum. Tubuli crasso corio ne minus duorum digitorum fiant, sed uti hi tubuli ex una parte sint lingulati, ut alius in alium inire convenireque possint. Coagmenta autem eorum calce viva ex oleo subacta sunt inlinienda, et in declinationibus libramenti ventris lapis est ex saxo rubro in ipso geniculo conlocandus isque perterebratus, uti ex decursu tubulus novissimus in lapide coagmentetur et primus [ex] librati ventris; ad eundem modum adversum clivum et novissimus librati ventris in cavo saxi rubri haereat et primus expressionis ad eundem modum coagmentetur. (*De arch.* 8.6.8)

> 8 But if we want less cost, it must be done thus. Let there be made terracotta pipes with a wall of no less than two fingers thick, but so that these pipes are "tongued" on one end so that one can fit into another and they can form a unit. Their joints, however, must be coated with quicklime worked up with oil, and in the slopes of the level of the *venter* a stone of red rock must be placed in the knee itself, and it must be drilled through, in order that the last pipe from the slope and the first from the level *venter* are connected in the stone; in the same manner at

> the facing slope let both the last of the level *venter* attach to the bore of the red rock and the first of the elevating section be connected in the same manner.

The term *libratus venter* describes a level portion at the bottom of an inverted siphon. In the reading *ex librati ventris* in the Loeb edition the case and the preposition do not match. The Budé edition omits the word *ex* from the sentence instead. Vitruvius describes in this passage concave vertical bends. As discussed above, bends oriented in such a way that the underground bears the forces resulting from static pressure were not as much in danger of bursting as convex bends that may be dislocated upwards, away from the ground. Pierced blocks that fit Vitruvius' description occur at Pergamum at the top of both intervening hills, where they anchored convex vertical bends in the pipeline (Garbrecht 1978: figs. 7-8).

> 9 Ita librata planitia tubulorum a vi decursus et expressionis non *extolletur*. Namque vehemens spiritus in aquae ductione solet nasci, ita ut etiam saxa perrumpat, nisi primum leniter et parce a capite aqua inmittatur et in geniculis aut versuris alligationibus aut pondere saburra contineatur. Reliqua omnia uti fistulis plumbeis ita sunt conlocanda. (*De arch.* 8.6.9)

> 9 Leveled in this way the even stretch of pipeline is not lifted up by the force of the descent or the ascent. For in the conduction of water, violent breath habitually forms so that it even breaks through rocks, unless the water from the head is at first admitted slowly and moderately and is contained at the bends and

> turns either by ties or by ballast. Everything else is to be arranged as in the case of lead pipes.

The corner segments at convex bends will be dislocated if the force pulls them away from the ground. The key word is *extolletur*. Rowland (Rowland, Howe *et al.* 1999) translates it as “displaced”, Morgan (Morgan 1960) as “sprung out”. The proper translation ought to read “lifted out”, implying an upward motion (Fig. 2.4). Forces acting on bends due to sudden admission of water, as Vitruvius describes, are considerable, but they do not reach the magnitude of the forces generated by static pressure. Nevertheless, Gandenberger (1957: 99) confirms that modern pipelines, too, are initially filled slowly in order to prevent possible damage due to sudden changes in momentum. “Alte Praktiker […] füllen ihre Rohrleitungen sehr langsam. Sie benötigen oft 2 bis 3 Tage für eine Rohrleitung von 6 bis 10 km Länge.” (Experienced practitioners [...] fill their pipelines very slowly. They often take 2 to 3 days to fill a pipeline of 6 to 10 km length.)

2.2 Hero of Alexandria

Hero’s work is not directly related to water supply technology, but his creative *automata* show a high level of technical skill and theoretical knowledge of water and air pressure. Not much is known about the life of this versatile person. In one of his treatises Hero discusses a method of determining the distance between Rome and Alexandria by timing the same lunar eclipse at both places. The only lunar eclipse that was visible from both Rome and Alexandria within a time period of five centuries occurred in A.D. 62, placing Hero’s *floruit* in the first century A.D. (Neugebauer 1938: 22; Drachmann 1948: 76-7; Keyser 1988: 220; Landels 2000: 201).

Hero wrote about mathematics and physics, surveying and mechanics. The different texts are uneven in quality. Parts of his *Mechanics* and of the *Pneumatics* are probably unfinished. He drew his information from earlier writers, most notably Ctesibius (Schmidt 1899: ix; Usher 1954: 98; Drachmann 1976: 2). The surviving descriptions of Hero’s *automata* contain line drawings that show the function of these mechanical devices. Hero describes not only practical devices such as surveying instruments and gearing mechanisms, but also gadgets that appear impractical from a modern point of view. They were perhaps objects for the demonstration of mechanical principles, working models that may or may not have been built also on a larger scale. One of Hero’s models, a rotating sphere with two angled nozzles propelled by steam, effectively anticipates the invention of the steam turbine (*Pneum.* 1.50). Other inventions open temple doors, refill wine cups and make mechanical birds sing.

Hero’s work illustrates the qualitative awareness of ancient engineers for the laws that govern the physical world around them. In the *Pneumatica* Hero describes a large number of gadgets that use the principles of both the true and the inverted siphon to achieve a desired effect.

The playful use of aerostatic and hydrostatic principles in these intricate devices shows that the application of these principles in large-scale structures such as inverted siphons cannot have been a matter of chance. The behavior of air and water in pipes was known and could be kept well under control on a small scale. It is reasonable to assume that the designers of ancient water pipelines were equally aware of possible problems and that they knew exactly how to solve them with the resources they had at their disposal. Hero suggested the use of a U-tube, *i.e.* a small-scale inverted siphon, for leveling a *dioptra* (Lewis 2001: 87). His “harmonious goblets” (*Pneum.* 14) make use of an inverted siphon to transport liquid from one vessel to another:

> If two vessels, both of them having visible outlets, stand upon a pedestal, and one of them be filled with wine, the other remaining empty, the wine shall not flow out until the empty vessel be filled with water; and then a discharge shall begin, of wine from one, and of water from the other, until both are empty. Such vessels are all called harmonious goblets. Let A B C D (Appendix: Fig. 0.1) be the pedestal on which the vessels, E and F, stand. In each of them place a bent siphon, G H K in E, and L M N in F, and let the outer extremities of the siphons be shaped like water-pipes. At the bend the siphons must approach nearly to the mouths of the vessels. Let another bent tube, X O P R, passing through the pedestal, connect the two vessels, the extremities of which, X and R, must reach as high as the bend of the siphons. Now pour wine into one vessel, taking care that it does not mount higher than the bend of the siphon at H. Up to this point the wine will not flow out, as there is nothing to originate a discharge through the siphon. But if we pour water into the vessel F, until its surface mounts above the bend of the siphon at M, then the water will descend and pass through the pipe X O P R into the other vessel. Thus a discharge is occasioned of the wine also, and both vessels will continue to run the one with wine, the other with water until both are emptied (trans. B. Woodcroft).

The principle of displacement of air by a liquid is demonstrated in *Pneum.* 19:

> If a goblet be placed upon a pedestal, whatever quantity may be drawn from it, it shall always continue full. The construction is as follows (Appendix: Fig. 0.2). Let A B be a vessel, the mouth of which is closed just at the neck, by the partition C D. Through C D let a tube, E F, be inserted, reaching nearly to the bottom; let another tube, G H, be passed through the bottom of the vessel, reaching nearly up to the partition C D; and in the bottom bore a hole, K, to admit the small tube K L. The vessel A B must stand upon a pedestal, M N O X, through which passes the projection of the tube G H, and another tube S T communicating with the pedestal and the goblet P R. Now let wine be poured through E F into A B (the air will pass out through G H), and, if the tube K L be left open, it will pass through into the pedestal and the goblet P R: but, if K L be closed, the vessel A B will be filled. Let, then, the wine run into the pedestal M N O X and the goblet P R, so that M N O X may be filled as high as the mouth of the tube G H. When this is done, close E, and the wine in A B will no longer flow through K L, for no more air can enter through E to supply the vacuum created. When, therefore, any wine is taken from the goblet, the orifice E must be unclosed, and, the air having found an entrance, the wine will flow again into the pedestal and goblet, until it is full. And this may be done as often as we draw off wine from the goblet. It will be requisite that a small hole be pierced in the side of the pedestal at U, that an equivalent bulk of air may pass into the vessel A B through the orifice G and the hole U (trans. B. Woodcroft).

Pneum. 24 shows that Hero was well aware that a bubble of compressed air forms at the top of a convex bend in a pipe:

> Let there be an empty vessel, and another containing wine: whatever quantity of water we pour into the empty vessel, the same quantity of wine and water mixed may be drawn off through a pipe in any proportion we please; such, for instance, that there may be two parts of water to one of wine. Let A B (Appendix: Fig. 0.3) be an empty vessel, either a cylinder or a rectangular parallelopiped: by the side of this, and on the same base, place another vessel, C D, perfectly air-tight, and, like A B, either a cylinder or a rectangular parallelopiped; but the base of A B must be twice as great as that of C D, as the water is to be the double of the wine. Near C D place another air-tight vessel, E F, into which the wine is to be poured; and between the vessels C D, E F, let a tube run, G H K, perforating and soldered into their coverings. In E F let there be a bent siphon, L M N, the inner leg of which must reach almost to the bottom of the vessel, leaving only a passage for the water, and the other, being bent within the vessel, lead into the next vessel, O X. From this vessel let the tube P R lead through all the vessels, or be carried under the pedestal on which they stand, that it may readily pass near the bottom of the vessel A B. Let another tube, T S, connect the vessels A B, C D, and near the bottom of A B place a small pipe, U, which with P R it must be included in a larger pipe, Q W, provided with a cock by means of which it may be opened or shut at pleasure. When these preparations have been made, close the pipe Q W, and pour water into the vessel A B; a part, viz. one half, will pass into C D,

through the tube S T, and the water which falls into C D will force out a mass of air equal to itself through G H K [This is where the air is compressed in a convex pipe bend. Similar to the water level rising in an inverted siphon during the filling process, the rising water level in vessel CD compresses the air volume above it and forces it through the bent tube GHK into vessel EF. The displaced air, then, presses down on the level of wine in vessel EF. The situation, therefore, parallels that occurring downstream from a local high point in an inverted siphon, where, likewise, a volume of air is enclosed by two columns of water.] into the vessel E F; in like manner this air will force an equal quantity of wine into the vessel O X through L M N. Now, if we open the pipe Q W, the water poured into the vessel A B and the wine carried out of O X through the tube P R will flow through it together and thus what was proposed will be done. The vessels will be empty again when, the mixed liquid having been all discharged, the air enters them through the tube P R (trans. B. Woodcroft).

Valves, too, were well known to Hero, as show *Pneum.* 11 and 20:

The following is the construction of the valve referred to. Take two rectangular plates of bronze of the thickness of a carpenter's rule, and measuring about one finger's breadth (7/10 of an inch) on each side. When these have been accurately fitted to each other, polish their surfaces so that neither air nor liquid may pass between them. Let A B C D, E F G H, (Appendix: Fig. 0.4) be the plates, and in the centre of one of them, A B C D, bore a circular hole about 1/3 of a finger's breadth (1/4 of an inch) in diameter. Then, applying the side C D to E F, let the plates be attached by means of hinges, so that the polished surfaces may come together. When the valve is to be used, fasten the plate A B C D over the aperture, and any air or liquid forced through will be effectually confined. For by the pressure exerted the hinges move, and the plate E F G H opens readily to admit the air or liquid; which when enclosed in the air-tight vessel, presses on the plate E F G H, and closes the aperture through which the air was forced in (trans. B. Woodcroft).

If it is desired to adapt this contrivance for use, so that from a goblet occupying any given position a considerable quantity of water may be drawn and yet the goblet remain full, proceed as follows. Let A B (Appendix: Fig. 0.5) be a vessel containing as much water as will probably be required, and C D a pipe leading from this into a trough beneath, G H. Near the pipe fix a lever beam, E F, and at the extremity E A suspend a piece of cork, K, so that it may float in the trough; at the other extremity F let a chain be fastened furnished with a leaden weight, X. Let the whole be so arranged that the cork, floating on the water in G H, closes the mouth of the pipe; yet that, when water has been drawn from the trough, the cork, being heavier than the weight at X, shall sink and open the pipe, so that the water may flow in again and raise the cork. Let L M be the goblet placed in any convenient position, its lip being on a level with the surface of the water in the trough when there is no discharge from the pipe owing to the floating cork: and let the tube H N lead from the trough into the bottom of the goblet. Now if, when

> the goblet is full, we draw water from it, we shall at the same time reduce the water in the trough; and the cork sinking will unclose the pipe, so that the water, flowing both into the trough and the goblet, will again raise the cork, and the discharge will cease. And this will happen as often as we remove water from the goblet (trans. B. Woodcroft).

Finally, Hero’s fire engine (*Pneum.* 28) shows that pistons were in use in water lifting devices.

> The siphons used in conflagrations are made as follows. Take two vessels of bronze, A B C D, E F G H, (Appendix: Fig. 0.6), having the inner surface bored in a lathe to fit a piston, (like the barrels of water-organs), K L, M N being the pistons fitted to the boxes. Let the cylinders communicate with each other by means of the tube X O D F, and be provided with valves, P, R, such as have been explained above, within the tube X 0 D F and opening outwards from the cylinders. In the bases of the cylinders pierce circular apertures, S, T, covered with polished hemispherical cups, V Q, W, Y, through which insert spindles soldered to, or in some way connected with, the bases of the cylinders, and provided with shoulders at the extremities that the cups may not be forced off the spindles. To the centre of the pistons fasten the vertical rods S E, S E, and attach to these the beam A' A', working, at its centre, about the stationary pin D, and about the pins B, C, at the rods S E, S E. Let the vertical tube S' E' communicate with the tube X O D F, branching into two arms at S', and provided with small

pipes through which to force up water, such as were explained above in the description of the machine for producing a water-jet by means of the compressed air. Now, if the cylinders, provided with these additions, be plunged into a vessel containing water, I J U Z, and the beam A' A' be made to work at its extremities A', A', which move alternately about the pin D, the pistons, as they descend, will drive out the water through the tube E' S' and the revolving mouth M'. For when the piston M N ascends it opens the aperture T, as the cup W Y rises, and shuts the valve R; but when it descends it shuts T and opens R, through which the water is driven and forced upwards. The action of the other piston, K L, is the same. Now the small pipe M', which waves backward and forward, ejects the water to the required height but not in the required direction, unless the whole machine be turned round; which on urgent occasions is a tedious and difficult process. In order, therefore, that the water may be ejected to the spot required, let the tube E' S' consist of two tubes, fitting closely together lengthwise, of which one must be attached to the tube X O D F, and the other to the part from which the arms branch off at S'; and thus, if the upper tube be turned round, by the inclination of the mouthpiece M' the stream of water can be forced to any spot we please. The upper joint of the double tube must be secured to the lower, to prevent its being forced from the machine by the violence of the water. This may be effected by holdfasts in the shape of the letter L, soldered to the upper tube, and sliding on a ring which encircles the lower (trans. B. Woodcroft).

These *automata* demonstrate that Hellenistic natural philosophers understood and controlled many principles and possible problems in relation to the flow of water in pipes. They understood the principle of water finding its own level in communicating tubes; they understood that there is a displacement of air by water when a vessel is filled, and that air must be able to enter when a water-filled vessel is emptied; finally they understood that a bubble of compressed air will form at the top of a convex bend in a pipe when the air is displaced by an inflowing liquid. Hero's *automata* are often described as toys with no practical application. Such an assessment does not take into account their potential applicability, though the view is not unique. The Renaissance scientist Roger Bacon described an invention as far-reaching as gunpowder in firecrackers as toy (Rice and Grafton 1994: 11). Tybjerg (2004: 27) has shown that the devices described in Hero's *Pneumatics* must be evaluated in the broader context of a dialogue between philosophy—the main tool in antiquity for the investigation and description of physical phenomena—and the practical demonstration of these phenomena: a contest between the Aristotelian "actuality" and "potentiality". For the purposes of this study the observation suffices that Hero's *automata* show a qualitative, though not a quantitative, understanding of all physical principles that are at work in inverted siphons.

2.3 Gaius Plinius Secundus

Born in A.D. 23, the elder Pliny, too, was successful in Roman public life as a military commander and administrator. His only surviving written work is the *Historia naturalis*. In 37 books Pliny draws together information on the natural world as it pertains to humans, "by perusing about 2,000 volumes […] 20,000 noteworthy facts obtained from one hundred authors…" (*NH* preface 17). He treats topics as diverse as astronomy, anatomy, zoology, botany, medicine, and mineralogy. In contrast to Frontinus' pragmatism, Pliny's work is frequently anecdotal. The information he gives varies widely in quality and credibility, depending on the sources he used himself. The writing of the *Historia naturalis* was completed in A.D. 77 (Feder 1998: 348). Pliny died near Stabiae in A.D. 79 during the eruption of Mount Vesuvius.

Only *NH* 31.57 and 58, in which Pliny describes methods of carrying water in pipes, are of immediate relevance to inverted siphons. Pliny does not list Vitruvius among the authors from whom he drew his information for these books. Vitruvius is mentioned, however, as a source for Book 36 on the nature of stones and on various building materials, remarkable buildings—including the aqueducts of Rome—and building construction in general. *NH* 31.57 and 58 complement the treatise on pipelines in Vitruvius' *De architectura*. It is instructive to read Pliny's recommendation for bringing a closed conduit up and down frequently if it comes from a long distance, "*ne libramenta pereant*" (lit.: "lest the level [momentum; pressure] be lost"; *NH* 31.57). Pliny's description fits well the layout of inverted siphons with intermediate high points, but his explanation of the function of the high points is problematic. Pliny ascribes to the towers a function similar to that of a pump, as if the momentum of flowing water could be kept constant by repeatedly bringing it up to a higher level. The First Law of Thermodynamics states, however, that energy cannot be created *ex nihilo* (Eastop and McKonkey 1986: 19-29). If water is flowing through a conduit, friction transforms part of its kinetic energy into heat. This dissipation of energy is the reason why water flowing through an inverted siphon will never rise to its own level, and why a tower in a conduit cannot serve as a reservoir for “new” energy to the water.

Pliny (*NH* 36.224) complements the Vitruvian text by recommending pine, spruce, or alder for the manufacture of wooden water pipes. Vitruvius does not mention wood as a possible pipe material, although such pipes are present in the archaeological record (Fabio and Fassitelli: 84; Tölle-Kastenbein 1990: 92; Hodge 1992: 111-12; 2000a: 62; Jansen 2000: 103-4, n. 1).

2.4 Sextus Iulius Frontinus

Born around A.D. 35, Frontinus had a spectacular career in politics and the military. He was elected consul four times and spent three or four years in Britain as provincial governor. Under Nerva, in A.D. 97, about six years before the end of his life, he was appointed *curator aquarum*, head civil servant in charge of the urban water works of the city of Rome. In this function Frontinus wrote his treatise on the aqueducts of the city, both for his own benefit and for that of his successors (*Aq.* 1.2). The text takes stock of his equipment and work force, pointing out technical, financial, and administrative details of the system and giving an overview of the history of Roman water supply. Recent work (DeLaine 1996; Saastamoinen 2000; Del Chicca 2004; Rodgers 2004) has pointed out the political dimension of Frontinus’ treatise and that it was not intended to be primarily a technical handbook.

Scholars (Blackman and Hodge 2001: 22; Bruun 2004: 342) have shown conclusively that flow rate cannot be determined from Frontinus’ tables of pipe sizes, despite ingenious earlier attempts at presenting a possible conversion of *quinaria* to modern values (Hodge 1984; Rodgers 1986). Frontinus’ work is a precise, albeit incomplete source of information on the water supply system of the city of Rome in the late first century A.D. The text contains no information about matters that go beyond the city of Rome, and no information on inverted siphons, although these must have been present in the urban distribution system (Blackman and Hodge 2001: 117-18, note 329). Inverted siphons were likely part of the Aqua Anio Vetus below Ponte Lupo (van Deman 1934: 61), the Aqua Marcia at Tibur (Stat. *Silv.* 1.3, 66-7), within the city bringing water up to the Capitoline Hill (van Deman 1934: 139; Ashby 1935: 152), and perhaps the Aqua Claudia on its route to the Palatine Hill (van Deman 1934: 267; Ashby 1935: 249-51; Blake 1968: 123, note 95). Hence, notwithstanding its uniqueness, Frontinus' text is of only marginal use for the examination of the systems in the Hellenistic kingdoms or in the Roman Empire outside of the city of Rome.

3. Vitruvius and the Greeks

This chapter points out nuances in the interpretation of some of Vitruvius' technical vocabulary in *De architectura*. Specifically, it examines the phrase *vis spiritus*, generally translated as "air pressure", by comparing it with its Greek equivalent, βία πνεύματος, in an attempt to come closer to the meaning of the untranslatable *hapax legomenon "colluviaria"*. The word *colluviaria* cannot be translated on etymological grounds, nor can it be understood by looking at the archaeological evidence. This is problematic because one would generally expect a technical text that deals with aqueducts, of which so many remains have been preserved, to fit the archaeological evidence relatively easily.

Book 8 of *De architectura* describes a broad range of aspects of water technology. Chapter 8.6 specifically deals with aqueducts and contains, next to a short reference by Pliny the Elder (*NH* 31.57-8), the only surviving ancient literary description of inverted siphons. Such a structure, Vitruvius tells us in the preceding passage, was known in Latin as *venter* or κοιλία in Greek. Both words mean belly. Vitruvius' description of an inverted siphon is notoriously difficult to translate and has caused much discussion among modern scholars.

The relevant passage from *De architectura* appears in book 8.6.6:

> 6 Quodsi non venter in vallibus factus fuerit nec substructum ad libram factum, sed *geniculus* erit, erumpet et dissolvet fistularum commissuras. Etiam in ventre colluviaria sunt facienda, per quae vis spiritus relaxetur. Ita per fistulas plumbeas aquam qui ducent, his rationibus bellissime poterunt efficere, quod et

> decursus et circumductiones et ventres et expressus hac ratione possunt fieri, cum habebunt a capitibus ad moenia ad fastigii libramenta. (*De arch.* 8.6.6)

> 6 If, however, neither a *venter* is built in the low portion nor a substructure to create a level, but the line forms a sharp convex bend instead, the bend will come apart and sever the joints between the pipe segments. Furthermore *colluviaria* through which pressure is released must be added in these places. If water is to be conducted through lead pipes, it will be best accomplished in this way because the descents, the detours, the *ventres,* and ascents can be realized by this method if the header tank and the city are on the same level.

Since Vitruvius used Greek sources, a look at the use of πνεῦμα–the Greek equivalent of *spiritus*–is instructive; an idea proposed by Lewis (2000: 349), but never carried out. Πνεῦμα is a valid Greek translation of the Latin *spiritus* (Ju 2007). The Stoic idea of πνεῦμα is that of an active principle that interpenetrates all matter, lifeless by nature, and endows living things with their characteristic properties.

> κατὰ δὲ τὸν Ἀθήναιον στοιχεῖα ἀνθρώπου οὐ τὰ τέσσαρα πρῶτα σώματα, πῦρ καὶ ἀὴρ καὶ ὕδωρ καὶ γῆ, ἀλλ’ αἱ ποιότητες αὐτῶν, τὸ θερμὸν καὶ τὸ ψυχρὸν καὶ τὸ ξηρὸν καὶ τὸ ὑγρὸν, ὧν δύο μὲν τὰ ποιητικὰ αἴτια ὑποτίθεται, τὸ θερμὸν καὶ τὸ ψυχρὸν, δύο δὲ τὰ ὑλικὰ, τὸ ξηρὸν καὶ τὸ ὑγρὸν, καὶ πέμπτον παρεισάγει κατὰ τοὺς Στωικοὺς τὸ διῆκον διὰ πάντων πνεῦμα, ὑφ’ οὗ τὰ πάντα συνέχεσθαι καὶ διοικεῖσθαι. (Pseudo-Galenus *Introductio seu medicus* 14.698)

> According to Athenaeus the components of a human body are not the first four elements, fire, air, water, and earth, but their qualities, heat, cold, dryness, wetness, of which he suggests that two, heat and cold, are active, and two, dryness and wetness, are passive. And he introduces a fifth, all-pervading one, according to the Stoics, *pneuma*, by which all is held together and controlled. (trans. Nikolic)

> The male semen, too, contains *pneuma*.

> πάντων μὲν γὰρ ἐν τῷ σπέρματι ἐνυπάρχει ὅπερ ποιεῖ γόνιμα εἶναι τὰ σπέρματα, τὸ καλούμενον θερμόν. τοῦτο δ᾿ οὐ πῦρ οὐδὲ τοιαύτη δύναμίς ἐστιν ἀλλὰ τὸ ἐμπεριλαμβανόμενον ἐν τῷ σπέρματι καὶ ἐν τῷ ἀφρώδει πνεῦμα καὶ ἡ ἐν τῷ πνεύματι φύσις, ἀνάλογον οὖσα τῷ τῶν ἄστρων στοιχείῳ. (Arist. *GA* 736b33-737a1)

> In all cases an animal’s seed contains that which makes it reproductive, the so-called hot substance. But this is not fire nor any power of that character, but the *pneuma* which is embraced in the sperm and its foam-like substance, which is analogous to the element of which the stars are composed. (trans. Harris)

Hence a translation of *vis spiritus* as merely “air pressure” falls short of the meaning that the word *spiritus* or its Greek equivalent πνεῦμα had in antiquity. In the English language, too, the word “spirit”, derived, of course, from the Latin *spiritus*, means something completely different than “breath”. While this divergence in meaning is also based on the Christian tradition of the Holy Spirit, subsequent to our time period of interest, it shows, nonetheless, that a broader investigation of the uses of this term is necessary for a proper understanding.

In Greek medicine, Erasistratus (fourth century B.C.), quoted by Galen in *De naturalibus facultatibus*, examined the pumping action of the heart and explained that arterial blood transported πνεῦμα to all parts of the body (Lindberg 1992: 121). The parallel of blood flow in an artery with water flow in a pipeline under pressure is obvious. The comparison raises the question of whether Vitruvius was more specifically thinking of oscillations in the water column during the filling process, inviting an even closer analogy with the cardio-vascular system. Ortloff and Kassinos (2003) demonstrated that such oscillations did indeed occur in the inverted siphon at Aspendos.

A comprehensive search in the TLG reveals that the words βία and πνεῦμα, Greek equivalents of *vis* and *spiritus*, occur in close proximity numerous times in various contexts, though the context and meaning of the surviving texts are not helpful for our purpose. Typical examples relate to the basic meaning of πνεῦμα, breath, such as in a passage on stammering in Aristotle’s ἐκ τοὺ περὶ ἀκουστῶν (*On things heard*).

> διὸ καὶ πολὺν χρόνον τὸ αὐτὸ ῥῆμα λέγουσιν, οὐ δυνάμενοι τὸ ἑξῆς εἰπεῖν, ἀλλὰ συνεχῶς τῆς κινήσεως καὶ τοῦ πνεύμονος αὐτῶν ἐπὶ τὴν αὐτὴν ὁρμὴν φερομένου διὰ τὸ πλῆθος καὶ τὴν βίαν τοῦ πνεύματος. (Arist. *Aud.* 804b, 33)

> Consequently they utter the same sound for a long time, not being able to make the next one, as the movement and the lung travel in the same direction owing to the quality and force of the breath. (trans. Hett, LCL)

> Other frequent occurrences relate to wind, such as in Polybius 1.44.4.4:

> οἱ δὲ Ῥωμαῖοι τὰ μὲν αἰφνιδίου γενομένης τῆς ἐπιφανείας, τὰ δὲ φοβούμενοι μὴ σὺν τοῖς πολεμίοις ὑπὸ τῆς βίας τοῦ πνεύματος συγκατενεχθῶσιν εἰς τὸν λιμένα τῶν ὑπεναντίων, τὸ μὲν διακωλύειν τὸν ἐπίπλουν τῆς βοηθείας ἀπέγνωσαν, ἐπὶ δὲ τῆς θαλάττης ἔστησαν καταπεπληγμένοι τὴν τῶν πολεμίων τόλμαν. (Plb. 1.44.1.1)

> Partly from astonishment at this sudden appearance, partly from dread of being carried along with the enemy by the violence of the gale into the harbour of their opponents, the Romans did not venture to obstruct the entrance of the reinforcement; but stood out at sea overpowered with amazement at the audacity of the enemy. (trans. Shuckburgh)

In both instances the term is used for air in motion—not necessarily under pressure. The usually inanimate Empedoclean element ἀήρ is set in motion, animated, and hence transformed into πνεῦμα. Empedocles’ description of breathing uses the simile of the clepsydra, an instrument for the transfer of liquids, consisting of a vessel with strainer-like perforations at the bottom and a tube at the top that could be opened or closed, is instructive for the difference between ἀήρ and πνεῦμα. The relevant passage occurs in fragment 100, edited by Diels and Kranz (1951), and is also repeated verbatim by Aristotle in *Resp.* 473b-474a:

> ὧδε δ’ ἀναπνεῖ πάντα καὶ ἐκπνεῖ· πᾶσι λίφαιμοι σαρκῶν σύριγγες πύματον κατὰ σῶμα τέτανται, καί σφιν ἐπὶ στομίοις πυκιναῖς τέτρηνται ἄλοξιν ῥινῶν ἔσχατα τέρθρα διαμπερές, ὥστε φόνον μέν κεύθειν, αἰθέρι δ’ εὐπορίην διόδοισι τετμῆσθαι. ἔνθεν ὁπόταν μὲν ἀπαΐξηι τέρεν αἷμα, αἰθὴρ παφλάζων καταΐσσεται οἴδματι μάργωι, εὖτε δ’ ἀναθρώισκηι, πάλιν ἐκπνέει, ὥσπερ ὅταν παῖς κλεψύδρηι παίζουσα διειπετέος χαλκοῖο—εὖτε μὲν αὐλοῦ πορθμὸν ἐπ’ εὐειδεῖ χερὶ θεῖσα εἰς ὕδατος βάπτηισι τέρεν δέμας ἀργυφέοιο, οὐδεὶς ἄγγοσδ’ὄμβρος ἐσέρχεται, ἀλλά μιν εἴργει ἀέρος ὄγκος ἔσωθε πεσὼν ἐπὶ τρήματα πυκνά, εἰσόκ’ἀποστεγάσηι πυκινὸν ῥόον· αὐτὰρ ἔπειτα πνεύματος ἐλλείποντος ἐσέρχεται αἴσιμον ὕδωρ. ὣς δ’ αὔτως, ὅθ’ ὕδωρ μὲν ἔχηι κατὰ βένθεα χαλκοῦ πορθμοῦ χωσθέντος βροτέωι χροῒ ἠδὲ πόροιο, — αἰθὴρ δ’ ἐκτὸς ἔσω λελιημένος ὄμβρον ἐρύκει, ἀμφὶ πύλας ἠθμοῖο δυσηχέος ἄκρα κρατύνων, εἰσόκε χειρι μεθῆι, τότε δ’ αὖ πάλιν, ἔμπαλιν ἤ πρίν, πνεύματος ἐμπίπτοντος ὑπεκθέει αἴσιμον ὕδωρ. ὣς δ’ αὔτως τέρεν αἷμα κλαδασσόμενον διὰ γυίων ὁππότε μὲν παλίνορσον ἀπαΐξειε μυχόνδε, αἰθέρος εὐθὺς ῥεῦμα κατέρχεται οἴδματι θῦον, εὖτε δ’ ἀναθρώισκηι, πάλιν ἐκπνέει ἶσον ὀπίσσω. (Arist. *Resp.* 473b-474a)

> This is the way all things breathe in and out. In all [animals] there are tubes of flesh, empty of blood, stretched all over the surface of the body, and over their openings the outermost surface of the skin is pierced through with close-packed

> holes, so that the blood is hidden but a free passage is cut through for the air (αἰθέρι) by these holes. When the blood rushes away from them, the air (αἰθὴρ) rushes in with a mad gush and when the blood runs back, the air breathes out (ἐκπνέει). It is like what happens when a girl plays with a clepsydra. When she closes the vent at the top and dips the clepsydra into the water, no water enters; it is prevented by the weight of air (ἀέρος) falling on the many holes of the strainer at the bottom until she unblocks the compressed [air-]stream (ῥόον); then, as the air leaves (πνεύματος ἐλλείποντος), the proper quantity of water enters. In the same way, when there is water in the clepsydra and the vent at the top is closed by the hand, air pressure from the outside (αἰθὴρ λελιημένος), exerted upwards on the strainer at the bottom, holds in the water until she lets go with her hand; then in turn, the opposite happens—as air enters (πνεύματος ἐμπίπτοντος) [through the vent at the top] the due amount of water flows out. In the same way, when the blood in the body rushes back again to the inmost part, a stream of air enters and when it runs back again an equal stream [of air] breathes out (ἐκπνέει) again. (trans. Furley)

Instructive in this passage is the differential use of the words αἰθήρ, ἀήρ, and πνεῦμα. In the simile of the clepsydra the ambient air outside of the vessel is the αἰθήρ (ll. 5, 7). The stationary air within the vessel, compressed by the water at the bottom and the girl’s thumb at the top, is referred to as ἀήρ (l. 13). Air in motion, however, entering or leaving the vessel, is called πνεῦμα (ll. 15, 21), the process of air entering or leaving the vessel is described by the verb πνέω (ll. 1, 8, and 25). Πνεῦμα, therefore, denotes air in motion, not stationary air. Transferring this notion to the meaning of *spiritus*, it is reasonable to say that in *De architectura* 8.6.6 Vitruvius does not speak of a compressed bubble of air, but rather of a quality of motion or tension. The argument is strengthened further by a passage from Tacitus *Ann.* 6.50.4-5:

> is velut propria ad negotia digrediens et per speciem officii manum complexus pulsum venarum attigit. neque fefellit: nam Tiberius, incertum an offensus tantoque magis iram premens, instaurari epulas iubet discumbitque ultra solitum, quasi honori abeuntis amici tribueret. Charicles tamen labi spiritum nec ultra biduum duraturum Macroni firmavit. (Tac. *Ann.* 6.50.4-5)

> This man, as if he were leaving on business of his own, clasped his hand, with a show of homage, and touched his pulse. Tiberius noticed it. Whether he was displeased and strove the more to hide his anger, is a question; at any rate, he ordered the banquet to be renewed, and sat at the table longer than usual, by way, apparently, of showing honour to his departing friend. Charicles, however, assured Macro that his breath was failing and that he would not last more than two days. (trans. Church)

In the scene described, Charicles, a Greek physician, touches Tiberius' arm to feel his pulse and thereupon states that the emperor's *spiritus*, here rendered in English as "breath", is failing. Oldfather (1939: 146) argues that one cannot feel the breath of a person by feeling the pulse at the wrist, and that, therefore, *spiritus* in this passage must be translated as “vitality”. In support of his argument he cites the *Corpus Hermeticum* 10.13:

> Τὸ πνεῦμα διῆκον διὰ φλεβῶν καὶ ἀρτηρίων καὶ αἵματος κινεῖ τὸ ζῷον καὶ ὥσπερ φόρτον τινὰ βαστάζει. (*Corpus Hermeticum* 10.13)

> Spirit pervading [body] by means of veins and arteries and blood, bestows upon the living creature motion, and as it were doth bear it in a way. (trans. Mead)

Πνεῦμα runs through veins and arteries along with blood and ought, therefore, not to be translated as breath or air but rather as a quality of the blood that is set in motion by the heart. The meaning of *spiritus* in the Tacitean passage, therefore, ought to be akin to the German word “Lebensgeist” (vital spirit).

An amusing occurrence of the lemma under investigation is in Aristophanes’ *Clouds*:

τί δῆτ᾽ ἐκεῖνος εἶπε περὶ τῆς ἐμπίδος;
Μα. ἔφασκεν εἶναι τοὔντερον τῆς ἐμπίδος
στενόν, διὰ λεπτοῦ δ᾽ ὄντος αὐτοῦ τὴν πνοὴν
βίᾳ βαδίζειν εὐθὺ τοὐρροπυγίου·
ἔπειτα κοῖλον πρὸς στενῷ προσκείμενον
τὸν πρωκτὸν ἠχεῖν ὑπὸ βίας τοῦ πνεύματος.
Στ. σάλπιγξ ὁ πρωκτός ἐστιν ἄρα τῶν ἐμπίδων.
ὢ τρισμακάριος τοῦ διεντερεύματος.

> ἦ ῥᾳδίως φεύγων ἂν ἀποφύγοι δίκην
> ὅστις δίοιδε τοὔντερον τῆς ἐμπίδος. (Ar. *Nu.*, 162)

> Strepsiades
>
> What, then, did he say about the gnat?
>
> Pupil
>
> He said the intestine of the gnat was narrow and that the wind went forcibly through it, being slender, straight to the breech; and then that the rump, being hollow where it is adjacent to the narrow part, resounded through the <u>violence of the wind</u>.
>
> Strepsiades
>
> The rump of the gnats then is a trumpet! Oh, thrice happy he for his sharp-sightedness! Surely a defendant might easily get acquitted who understands the intestine of the gnat. (trans. Henderson, LCL)

In this passage the term βία πνεύματος is applied to flatulence—a suitable context, given that Vitruvius calls the inverted siphon *venter* or κοιλία, *i.e.* belly. In the *Clouds*, the "violence of the wind" creates a sound at the narrow part of the rump, where it is hollow (κοῖλον). It is possible that gurgling sounds emanating from a pipeline during the filling process may have been likened to some intestinal problem in the human body. Nonetheless, it does not shed any new light on *colluviaria*. The Latin terms commonly used for flatulence are *flatus* and *crepitus*, as in the examples below.

> tum isti Graeci palliati, capite operto qui ambulant,
> qui incedunt suffarcinati cum libris, cum sportulis,
> constant, conferunt sermones inter se drapetae,
> obstant, obsistunt, incedunt cum suis sententiis,
> quos semper videas bibentes esse in thermipolio,
> ubi quid subripuere: operto capitulo calidum bibunt,
> tristes atque ebrioli incedunt: eos ego si offendero,
> ex unoquoque eorum exciam crepitum polentarium. (Plaut. *Curc*. 2.3.16)

> Yes, and as for those Greeks that stroll about with muffled heads and stalk along with their clothes bulged out by books and provision baskets, renegades that stand bout together, palaver together, block your road, set themselves in your way, stalk along with their sage observations, fellows you can always see guzzling in a tavern when they've stolen something—muffling their wretched heads and taking hot drinks, then stalking along grave of face and half seas over!—well, if I bump up against them, I'll knock some porridge-fed wind out of every one of their bodies. (trans. Nixon, LCL)

> quam multa ex uno verbo tuo! te adversus me omnia audere gratum est; ego servo et servabo (sic enim adsuevi) Platonis verecundiam. itaque tectis verbis ea ad te scripsi, quae apertissimis agunt Stoici; sed illi etiam crepitus aiunt aeque liberos

ac ructus esse oportere. Honorem igitur K. Martiis. tu me diliges et valebis. (Cic. *Fam.* 9.22.5)

What a long commentary on a single word of yours! I am pleased that you have no scruple in saying anything to me. For my own part I maintain and shall maintain Plato's modesty: and accordingly, in my letter to you, I have expressed in veiled language what the Stoics express in the broadest: for they say that breaking wind should be as free as a hiccough. All honour then to the Kalends of March! Love me and keep yourself well.

Eleganter Demetrius noster solet dicere eodem loco sibi esse voces inperitorum, quo ventre redditos crepitus. (Sen. *Ep*. 91.19)

Our friend Demetrius is wont to put it cleverly when he says: “For me the talk of ignorant men is like the rumblings which issue from the belly.” (trans. Gummere, LCL)

dicitur etiam meditatus edictum, quo ueniam daret flatum crepitumque uentris in conuiuio emittendi, cum periclitatum quendam prae pudore ex continentia repperisset. (Suet. *Cl. 32)*

> It is said, too, that [Claudius] intended to publish an edict, “allowing to all people the liberty of giving vent at table to any distension occasioned by flatulence,” upon hearing of a person whose modesty, when under restraint, had nearly cost him his life.

> onopradon cum ederunt, asini crepitus reddere dicuntur. (Plin. *NH* 27.87)

> Asses are said, if they have eaten onopradon, to break wind. (trans. Jones, LCL)

Spiritus, too, is used occasionally to mean “flatulence”. Pliny the Elder writes about the properties of radishes:

> Et vis mira colligendi spiritum laxandique ructum. (Plin. *NH* 19.78)

> They have a remarkable power of causing flatulence and eructation. (trans. Rackham, LCL)

Celsus describes the symptoms of a diseased kidney. Among other symptoms:

> […] urinae crebra cupiditas sed magna difficultas est, et quod inde excretum est, aquae simile vel rufum vel pallidum est, paulum tamen in eo levamenti est, alvus vero cum multo spiritu redditur, utique in renibus vitium est. (Celsus *Med.* 2.7.12)

> […] when there is frequent desire to urinate but great urinary difficulty, and when what is passed is like water, reddish or pallid, yet is followed by little relief, and much wind too is passed with a motion […] the kidneys are the seat of disorder. (trans. Spencer, LCL)

Elsewhere Celsus writes of diarrhea:

> Ipsa autem deiectio sine ulla noxa est, quae sine febre est, si celeriter desinit, si contacto ventre nullus motus eius sentitur, si extremam alvum spiritus sequitur. (Celsus *Med.* 2.8.12)

> Diarrhoea is itself harmless, when there is no fever, if it is quickly over, if on touching the abdomen no movements are to be felt, if wind follows the last of the motion. (trans. Spencer, LCL)

As πνεῦμα in the passage from Aristophanes, in these Latin texts *spiritus* is used to describe flatulence. The context of bodily functions is evident, in particular their malfunction. The windpipe is supposed to breathe, not the intestine. *Spiritus* in connection with the intestine is problematic, negative, indicative of a disease, and requires remedy. The medical author Celsus uses the word *spiritus* for flatulence, while the non-scientific authors appear to prefer *crepitus*. Pliny the Elder uses both terms, *crepitus* for an animal, *spiritus* for a person. Perhaps this observation is indicative of a similar difference as that between “fart” and “wind” in English—one vulgar, the other polite, because one describes the manifestation, the other the condition.

It is instructive to examine Greek medical texts for their use of the relevant terminology. It is reasonable to suggest that Vitruvius and his sources used similes from medicine or otherwise related to the human body for the description of technical details. After all, Vitruvius quotes Polycleitus’ *canon* of architectural proportions derived from the human body in book 3 of *De architectura*. In their interpretation of the human pulse the Pneumatic School of Greek medicine defined different types of pulse in the Pseudo-Galenic *Definitiones medicae*. One distinction was between a hard and a soft pulse.

> Σκληρός ἐστι σφυγμὸς ἐφ’ οὗ νευρώδης, ὡς ἂν εἴποι τις, καὶ ἀπόκροτος ἡ ἀρτηρία φαίνεται καὶ τὸ ἐνὸν πνεῦμα τεταμένον ὥστε καὶ τὴν πληγὴν ἔχειν τι ἀποπληκτικόν. Μαλακὸς σφυγμός ἐστιν ὁ ὑπεναντίος τῷ σκληρῷ ἀνειμένην καὶ ἁπαλὴν ἔχων τὴν ἀρτηρίαν. καὶ τὸ ἐνὸν πνεῦμα ἐκλελυμένον καὶ τὴν πληγὴν προσηνεστέραν. (Ps.-Gal. *Definitiones medicae* 19.405.1)

> Hard is the pulse in which the artery appears like sinew, as it were, and beaten hard and the pneuma within is tense so that the beat, too, has something apoplectic. The soft pulse is the opposite of the hard, the artery being relaxed and soft. And the pneuma within is relaxed and the beat gentle.

In this passage we find two terms occurring in Vitruvius. The pulse is hard when the πνεῦμα within the artery is tense. A soft pulse has a relaxed πνεῦμα in a soft artery. It is just this, the relaxation of the πνεῦμα/spiritus in the aqueduct pipeline, that Vitruvius wants to achieve by means of his *colluviaria*: to avoid the strain that a tense πνεῦμα exerts on the pipe as on the artery.

Erasistratos recognized the dependence of the pulse on the heartbeat and ascribed the expansion of the arteries to the pneuma propelled by the heart in systole.

> ὥς δὲ Ἐρασίστρατος ἔλεγεν, ὁ σφυγμὸς γίνεται φορᾷ τοῦ παρὰ καρδίας ἐπιπεμπομένου πνεύματος διὰ τῶν ἐν ταῖς ἀρτηρίαις κοιλοτήτων. (Gal. *Synopsis librorum suorum de pulsibus*. 9.508.1)

> As Erasistratos said, the pulse is created by the rush of the pneuma sent by the heart through the concavities in the arteries.

Elsewhere:

> ὥς κατὰ μίαν ἔνθλιψιν τῆς ἀρτηρίας ἐξικνεῖσθαι μέχρι τῶν κατὰ τοὺς πόδας ἄκρων τὴν φορὰν τοῦ πνεύματος, ὑπὲρ τοὺς σφοδροτάτους ἀνέμους τὸ τῆς φορᾶς τάχος εἶναι βουλόμενος. (Gal. *De loc. aff.* 8.316.12)

> … as with each compression of the artery the rush of pneuma reaches all the way to the furthest point of the feet, and the speed of the rush wants to be swifter than the most violent winds.

These passages again illustrate the similarity between Vitruvius' use of *spiritus* and the use of πνεῦμα by the Greeks. The transport of πνεῦμα, propelled by the heart, causes a dilation of the blood vessel. The πνεῦμα in the aqueduct pipe exerts the same type of strain on the pipe itself, and therefore it is necessary to relax it, especially, as we are told, the πνεῦμα can be swifter than the most violent winds. This passage is remarkably similar to Vitr. *De arch.* 8.6.9: *Namque vehemens spiritus in aquae ductione solet nasci, ita ut etiam saxa perrumpat.* “For a strong *spiritus* (translated as: “current of air”: Granger, Morgan; “air pressure”: Humphrey, Oleson, and Sherwood; “Luftdruck”: Fensterbusch; “pressure”: Rowland) usually arises in the passage of water, so that it even breaks through rocks.” It is interesting to note that Erasistratos, quoted by Galen, chooses to compare the strength of πνεῦμα to a violent wind and not to, say, a fast-flowing river. Πνεῦμα is created from air, though πνεῦμα itself is not air.

> ἕλκεται τοιγάρτοι τὸ πνεῦμα ἔχοθεν ὑπο τοῦ στόματος καὶ τῶν μυκτηρῶν, καὶ διὰ τῆς τραχείας ἀρτηρίας φέρεται εἰς πνεύμονα καὶ καρδίαν, ἔτι δὲ θώρακα· […] ὅν γὰρ τρόπον κατατάσσεταί τι εἰς τὰ σώματα ἀπὸ τοῦ εἰπνεομένου, τὸν αὐτὸν τρόπον καὶ τῷ πμεύματί τινα προστίθεται ἀπὸ τῶν σωμάτων καὶ πλείονά γε, ἅτινα καὶ πλεῖον ἀποτελεῖ τὸ ἐκπεμπόμενον πμεῦμα. (*Anonymus Londinensis* 23, J.89)

> Now pneuma is drawn in from the outside by the mouth and the nostrils and is carried through the rough artery, the windpipe, into the lung and the heart and also the thorax; […] for in the same way that some of that which is breathed in is allotted to the body, something is also added from the body to the pneuma, more in fact than is absorbed by it. (trans. Harris)

A passage from Seneca is reminiscent of the Vitruvian warning against the force of the *spiritus*:

> Corpus nostrum et sanguine irrigatur et spiritu, qui per sua itinera decurrit. Habemus autem quaedam angustiora receptacula animae per quae nihil amplius quam meat, quaedam patentiora in quibus colligitur et unde diuiditur in partes. Sic hoc totum terrarum omnium corpus et aquis, quae uicem sanguinis tenent, et uentis, quos nihil aliud quis quam animam uocauerit, peruium est. Haec duo aliubi currunt, aliubi consistunt. Sed quemadmodum in corpore nostro, dum bona ualetudo est, uenarum quoque imperturbata mobilitas modum seruat; ubi aliquid aduersi est, micat crebrius et suspiria atque anhelitus laborantis ac fessi signa sunt: ita terrae quoque, dum illis positio naturalis est, inconcussae manent; cum aliquid peccatur, tunc uelut aegri corporis motus est, spiritu illo qui modestius perfluebat icto uehementius et quassante uenas suas. (Sen. *QN* 6.14.1-2)

> Our body is irrigated by blood; also by *spiritus*, which runs along by its own routes. However, we have some rather narrow receptacles for breath [*animae*] through which *spiritus* does nothing more than pass, others wider in which the *spiritus* is collected and from there distributed to the parts of the body. In the same way this whole body of the entire earth is a passageway both for water, which takes the place of blood, and for winds [*ventis*], which you might call simply respiration [*animam*]. These two elements run together in some places, are stationary in other places. But in our body the movement of the veins also

> preserves its rhythm undisturbed while there is good health but when there is something wrong the movement pulses more rapidly and inhaling and exhaling give signs of effort and exhaustion. In the same way the earth remains unshaken as long as its condition is normal. When something is wrong, then there is motion just like that of a sick body, because the *spiritus* which was flowing through it in an even pattern is struck violently and causes its veins to shake. (trans. adapted from T. H. Corcoran, LCL, who translates *spiritus* as “air”)

Seneca compares the earth and its cavities filled with water and winds with the human body, where blood takes the place of water and *spiritus* takes the place of winds. It was obviously common to draw parallels between natural phenomena and phenomena taking place within the body. Ovid, too, in the myth of Pyramus and Thisbe, compares the flow of blood with the flow of water in a pipe.

> Ut iacuit resupinus humo, cruor emicat alte,
> non aliter quam cum vitiate fistula plumbo
> scinditur et tenui stridente foramine longas
> eiaculatur aquas atque ictibus aera rumpit. (Ov. *Met.* 4.121-4)

> As he lay stretched upon the earth the spouting blood leaped high; just as when a pipe has broken at a weak spot in the lead and through the small hissing aperture sends spurting forth long streams of water, cleaving the air with its jets. (trans. Miller, LCL)

In the simile of the body Seneca compares the *spiritus* with wind, showing that the two are related, though not identical. This comparison is another indication that *spiritus* and air are different things and cannot be used as synonyms. If the *spiritus* in the body is struck, it is an indication of sickness, causing the veins to shake. This phenomenon is the same as that of which Vitruvius warns in his passage in *De architectura* 8.6.9. The *spiritus* can grow so strong that it can even break rocks. The condition is undesirable and requires intervention. Once again, I believe it is too imprecise to render *spiritus* as “air”. The word expresses more than just the element, it means a vital force akin to the Greek πνεῦμα.

It is hard to know what definition of *spiritus* Vitruvius had exactly in mind when he warned of its destructive effects on a pipeline. But under the assumption that he understood the hydraulics underlying an inverted siphon, the comparison with πνεῦμα, the Greek equivalent of *spiritus* in Greek medical texts, shows that his *spiritus* does not mean simply air. The use of κοιλοτής for the concavity of a blood vessel is, furthermore, interesting as it demonstrates that κοιλία not only means the structure that we today call inverted siphon, but may in addition mean the pipe itself. These notions do not provide the expected insight into what *colluviaria* were, but the comparison with descriptions in Greek medical texts of blood flow is informative as it reveals the complexity behind the proper translation of a seemingly simple term such as *vis spiritus*. It shows the importance of casting one’s nets more widely when investigating the meaning of these difficult passages from *De architectura*, especially given the obvious models in Greek literature. The selected passages demonstrate that further investigation of Greek texts has much promise. Whether such an investigation will lead to a reasonable translation of *colluviaria*, is hard to predict. It is conceivable that Vitruvius made up the word to render in Latin some Greek technical term with no prior Latin equivalent. Cicero, who wrote earlier in the same century as Vitruvius, states in *de orat.* 1.155 that he did just that when he translated works by Greek orators into Latin:

> [155] Postea mihi placuit, eoque sum usus adulescens, ut summorum oratorum Graecas orationes explicarem, quibus lectis hoc adsequebar, ut, cum ea, quae legeram Graece, Latine redderem, non solum optimis verbis uterer et tamen usitatis, sed etiam exprimerem quaedam verba imitando, quae nova nostris essent, dum modo essent idonea. (Cic. *De orat.* 1.155)

> [155] Afterwards I resolved,—and this practice I followed when somewhat older,—to translate freely Greek speeches of the most eminent orators. The result of reading these was that, in rendering into Latin what I had read in Greek, I not only found myself using the best words—and yet quite familiar ones—but also coining by analogy certain words such as would be new to our people, provided only they were appropriate. (trans. Sutton, LCL)

A search of the TLG for a Greek equivalent of *colluviaria*, beginning with συν-, συμ-, συλλ-, or συγ- (or the same prefixes beginning with the letter ξ) to render the Latin prefix *coll-* in close proximity (within one line) of βία and πνεῦμα yielded no compelling results. I wish to suggest, however, the possibility that Vitruvius may have attempted to translate some noun associated with the Greek verb συλλύω, “to help in loosing” or “to solve difficulties”—a meaning relatively close to that of *relaxo* in Latin. The relevant entry in Liddell and Scott is:

> συλλύω,
>
> **16.** *help in loosing*, ξύλλυε μητρὸς δεσμόν E. *Andr.*723 :-- Med., τῷ Πριάμῳ συλλυσόμενοι τὸν παῖδ’ *assist* him *in redeeming* . . , Ar. *Fr.*678.
>
> II. *solve difficulties, settle, put an end to*, τὰ νείκη, τὸν πόλεμον , D.S.3.64, 29.22; ς. τινάς *reconcile* them, *IG*7.21.8 (Megara, ii B.C.), cf. *SIG*599.13 (Priene, ii B.C.), *Klio* 18.281 (Delph., ii B.C.), Phld.*Rh.*1.268 S.; and so prob. S.*Aj.*1317, ἐι μὴ ξυνάψων, ἀλλὰ συλλύσων πάρει not to stir conflict, but *to reconcile*:-- Med. And Pass., *come to a settlement*, πρός τινα D.S.12.4 ; τισι LXX *1 Ma.*13.47; ἐπὶ πᾶσι τοῖς δικαίοις ib.*2 Ma.*11.14.
>
> III. in A.*Ch.* 294, δέχεσθαι δ’ οὔτε συλλύειν τινά, Sch. Expl. Συλλύειν by συγκλύειν (leg. Συγκαταλύειν), συνοικεῖν, *rest under the same roof.*

The associated Greek noun σύλλυσις means “settlement”, “agreement”, or “treaty” and was used in that sense in inscriptions in Miletus, Olympia, Crete, Delos, and Epidaurus, as well as in Diodorus Siculus 12.4.5: [5] διόπερ οἱ περὶ τὸν’ Αρτάβαζον καὶ Μεγάβυζον ἔπεμψαν ἐις τὰς’ Αθήνας πρεσβευτὰς τοὺς διαλεξομένους περὶ συλλύσεως. “Consequently Artabazus and Megabyzus sent ambassadors to Athens to discuss a settlement.” The suggestion that *colluviaria* may be related to the Greek verb σύλλυω is based on speculation, but in view of the preceding discussion it is not without merit and is apt to contribute to the discussion about the origin of the Vitruvian term.

4. Archaeological Evidence

The physical remains of ancient long-distance pipelines are primary evidence for an attempt to investigate their individual design and identify solutions to potential problems posed by the topography. It is necessary to collect information about their context and layout in order to recognize similarities that may lead to explanations about the choice of one design feature over another. De Montauzan (1909) pointed out similarities between the inverted siphons at Aspendos and at Yzeron. The reconstruction of the poorly preserved tower "Tourillon de Craponne" follows, in fact, the model of the two towers at Aspendos. Based on the existence of intermediate high points in their course, Kessener (2000a) compares the technical data of the inverted siphons at Aspendos, Yzeron, and Pergamum. Lewis (1999) juxtaposes the systems at Pergamum, Smyrna, and Alatri, based on their closeness in construction date, but also because of the incorporation of natural hills into their course. Burdy (2002a) compares the nine inverted siphons that supplied Roman Lugdunum with water. The collection and comparison of raw data lays the ground work for a thorough investigation of these systems. Inverted siphons with intermediate high points have attracted scholarly attention because of the prominent remains at Aspendos. No study, however, has collected and presented side by side the technical information from all seven systems discussed in this dissertation. The following compilation of raw data from previous research is, therefore, an original and necessary basis for a more thorough investigation of inverted siphons and their technological, political, and social context. Hodge (1992: 428, n. 43) lists 16 inverted siphons from the Hellenistic and 25 from the Roman period. Due to the generally poor state of preservation of many remains more inverted siphons may be recognized in the future. Publication in languages other than English, French, Italian, or German may also be a reason for the relative obscurity of identified inverted siphons. Thus the structure at Segóbriga is not mentioned in Hodge’s list. The compilation in the framework of this project reassesses previous scholarly work and expands it by including in the collection the little known aqueducts at Segóbriga in Spain and Methymna on the island of Lesbos. The following chapters contain detailed descriptions of seven sites from classical antiquity that were supplied by long-distance pipelines. These seven aqueducts have in common the deliberate incorporation of intermediate high points, be they man made or natural. The following table summarizes the basic technical information contained in these site descriptions. The aqueduct at Methymna does not occur in the table due to the lack of almost all technical information about the aqueduct at that particular site.

	Pergamum	Smyrna	Alatri
Date	197 – 159 B.C.	2nd c. B.C.; before 85 B.C.	2nd half 2nd c. B.C.
Length of Aqueduct	42 km	24 km	?
Length of Inverted Siphon	*ca.* 3.5 km	*ca.* 4 km	3.3 km
Altitude of Header Tank	376 m (a. s. l.)	188 m (a. s. l.)	490 m (a. s. l.) (481 m?)
Altitude of Intermediate High Points	234 m and 235 m (a. s. l.)	161 m, 136.6 m and 112 m (a. s. l.)	455 m and 465 m (a. s. l.)
Altitude of Receiving Tank	335 m (a. s. l.)	183 m (a. s. l.)	473 m (a. s. l.) (479 m?)
Hydraulic Gradient	1.2%	*ca.* 0.13%	0.5%
Internal Pipe Diameter	0.22 m?	0.23 m	0.1-0.15 m?
Pipe Material	lead	terracotta and stone	lead
Number of Pipes in Parallel	1	?	?

	Yzeron	Segóbriga	Aspendos
Date	20 – 10 B.C.	mid-1st c. A.D.	2nd to 3rd c. A.D.
Length of Aqueduct	40 km	7 km	19 km
Length of Inverted Siphon	5.8 km	*ca.* 2.5 km	1.7 km
Altitude of Header Tank	313 m (a. s. l.)	870 m (a. s. l.)	47 m (relative to main *venter*)
Altitude of Intermediate High Points	306 m (a. s. l.)	840 m and 832 m (a. s. l.)	40 m and 38 m (relative to main *venter*)
Altitude of Receiving Tank	273 m (a. s. l.)	830 m	32 m (relative to main *venter*)
Hydraulic Gradient	0.7%	1.3%	0.8%
Internal Pipe Diameter	0.18 m?	0.1 m?	0.28 m
Pipe Material	lead	Lead	sand stone
Number of Pipes in Parallel	6-7?	1	1

Table 4-1a, b: Summary of Basic Pipeline Data

5. Pergamum

5.1 Location

The site of ancient Pergamum is located at 39°07′N latitude and 27°11′E longitude, immediately north of the modern city of Bergama in northwestern Anatolia, 110 km north of Izmir, 25 km inland from the Aegean Sea. The central Anatolian plateau forms the heartland of the Asian portion of Turkey. Some narrow strips of low-lying land can be found where the Anatolian plateau descends westward to the Aegean Sea. These areas frequently consist of plains or valleys formed by rivers that flow westward from the plateau into the Mediterranean Sea. The Kaikos River (modern Bakır Çay) has formed one such plain that is some 12 km wide. The city-hill of Pergamum, a block of andesite rock rising 300 m above the plain to an elevation of 335 m a.s.l., is located spectacularly on the north side of the Kaikos valley (Appendix: Fig. 0.7). The north, east, and west sides of the hill are very steep. The slope of the south side is less precipitous and allowed construction on various levels. The mountains located a few kilometers north of Pergamum rise to elevations of more than 1,300 m a.s.l. The Selinus River (modern Bergama Çay) and the Cetius River (modern Kastel Çay) flow north to south, the former on the west side, and the latter on the east side of Pergamum. Their joint waters flow into the Kaikos River 5 km south of Pergamum.

5.2 Climate

Recent climate data is produced, for example, jointly by the National Climatic Data Center and Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory under the framework of the Global Historical Climatology Network (GHCN), and is available online (Hoare 2006). Data for average temperatures at the weather station at Bergama, located at 45 m a.s.l., are derived from GHCN 2 Beta over a period of 336 months between 1963 and 1990:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	6.8	7.9	10.0	14.4	19.2	23.7	25.9	25.6	22.5	17.3	12.4	8.8	16.2

The weather station at Bergama does not provide any precipitation data. The station at Izmir, however, is located sufficiently close and in a sufficiently similar geographical setting to allow the assumption that the average precipitation in Smyrna and in Bergama is probably similar.

The data for Izmir, derived from GHCN 1, show an annual average of 674.9 mm calculated over 1175 months between 1864 and 1989.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	126.9	94.5	76.3	41.7	32.1	9.8	2.8	2.8	15.6	45.2	87.7	135.3	674.9

At Bergama, the climate is typically Mediterranean, with hot, dry summers (hottest month: July, at 25.9°C) and damp, mild winters (coldest month: January at 6.8°C). According to Walter and Lieth (Heinrich and Hergt 1990: 18-19), a month is classified as arid if the region receives less precipitation than would satisfy the climatological demand for evaporation. In concrete terms, a month in a given region is considered arid if the average rainfall accumulation in mm is less than twice the average temperature in °C. It follows that at Bergama the months of May through September must be considered arid.

5.3 History

Ceramic shards resembling Minyan ware from Troy, found on the slopes of the Pergamene hill, indicate that early datable human activity in the area took place in the second or early first millennium B.C. The earliest surviving stretch of fortification wall at Pergamum dates to the Archaic period (Radt 2001: 43). Until 546 B.C., the region around Pergamum was part of the Lydian kingdom and fell to Persia after the defeat of Croesus at the hands of Cyrus II (Garbrecht 1987a: 11).

In the 330s B.C. Pergamum became part of the empire of Alexander the Great, and for some time it was the residence of Alexander's illegitimate son Heracles and the latter's mother, Barsine. After the Battle of Ipsos, in 301 B.C., western Asia Minor came under the control of Lysimachos. The location of Pergamum on a 300 m high acropolis made it an ideal place for Lysimachos to store and guard part of Alexander's war treasury (Garbrecht 1987a: 11). Lysimachos made Philetairos garrison commander at Pergamum. Around 282 B.C., Philetairos deserted Lysimachos and offered his services and the fortress of Pergamum to Seleukos (Pausanias 1.10.3-4; Strabo 13.4.1). Seleukos was killed in the following year by Ptolemy Keraunos, an event that left Philetairos in control of the stronghold for 20 years. Philetairos became the first ruler of the Attalid dynasty, as he and his successors came to be called. Philetairos' nephew Eumenes succeeded him to the rule of Pergamum as Eumenes I (263-241 B.C.) (Strabo 13.4.1).

During the reign of the Attalid dynasty (281-133 B.C.), Pergamum became one of the wealthiest states of the ancient world. The territory came to include all of the former Persian satrapy of Mysia, allowing safe access to the Aegean Sea. Industry and agriculture flourished. From the beginning the Attalids "recognized the importance of art and architecture as vehicle to express the character, policies, and achievements of state" (Pollitt 1986: 79)—a concept that was, no doubt, important because the Attalids were usurpers. The inhabited area on the city hill grew under Philetairos and Eumenes I, *i.e.* between 281 and 241 B.C., from 5 ha to 21 ha (Garbrecht 1987a: 12). Philetairos had a fortification wall of ashlar masonry built more or less on top of the Archaic wall. Probably likewise under Philetairos, a roughly rectangular grid of streets was built, with channels or sewers (either rock-cut or in ashlar masonry, *ca*. 0.8 m deep and 1 m wide, covered with slabs) in the four main streets that ran downhill, allowing efficient drainage of the winter rains (Radt 2001: 45-7).

Under Eumenes II (197-159 B.C.), Pergamum became a dominant economic, cultural, and—due to its alliance with Rome—political power in the eastern Mediterranean region. The area of the city grew to the lower levels of the hill in the south and the east, so that it reached a size of 90 ha. The population size was probably between 20,000 and 40,000 inhabitants (Garbrecht 1987a: 18). The citadel was completely reshaped by means of artificial terraces, and the most famous monuments of the city, in particular the Altar of Zeus, were built during this period. The theatre that is visible today probably took shape also under Eumenes II, presumably built on an older structure. A new street system, aligned with the Athena Temple on a strictly rectangular grid, with *insulae* 92 x 58 m in size, replaced the old streets built by Philetairos. The nurturing of science and the arts found expression not only in the build-up of the famous library, which contained some 200,000 volumes, but also in the sculptural program of Pergamum (Pollitt 1986: 79; Garbrecht 1987a: 15; Radt 2001: 47-9).

Topographically, the city consisted of a number of distinct levels that were linked by a winding main street. The vertical distance from the lowest gate to the top of the acropolis was 275 m. The ascent was also symbolic, from primarily mundane structures on the lowest level to primarily religious structures on the highest level of the city. The city was entered through the south gate, or Gate of Eumenes. The first significant building as one passed through the gate was a market complex, the Lower Agora. The main street departed from the east corner of the agora and then ascended to a terraced complex of three interconnected gymnasia, two *temenoi* (of temples to Hera and to Demeter), and a fountain house. The gymnasia were built probably not later than the second half of the third century B.C. In the Hellenistic period, baths were housed in the upper gymnasium and required a significant amount of water (Akurgal 1990: 97). The main street ran past the precinct of Demeter north to the Upper Agora, the southernmost point of the acropolis proper. The buildings on the acropolis were spectacularly arranged in a semi-circular shape with the orchestra of the theater as the center point. A 250-m-long street lined with stoas formed the base line west of the semi-circle of the theater. The street crowned a massive retaining wall that ended north of the theater at the Temple of Dionysos, later the Temple of Caracalla. The fan-like shape of the *cavea*, built into the precipitous west flank of the hill, was reflected by the arrangement of buildings above, facing west into the widening plain of the Kaikos River and towards the Aegean Sea (Pollitt 1986: 233; Akurgal 1990: 92-3; Owens 1991: 87).

In 133 B.C., Pergamum was bequeathed to Rome by Attalos III and became part of the province of Asia (Schäfer 1976: 688). A period of 350 years followed during which Pergamum was politically insignificant, but still a culturally important city. Pergamum lost its character as a fortress and became an open city with 160,000 inhabitants (Garbrecht 1987a: 15). A new period of prosperity for Pergamum began during the reigns of Trajan and Hadrian (A.D. 98 – 138). It saw the construction of the Temple of Trajan, supported by an extensive system of vaults on the acropolis, an expansion of the Asklepieion, construction of the “Red Hall,” a Roman theater, stadium, and amphitheater in the Kaikos plain. The grid system of the streets changed orientation once again to align with the axes of the Temple of Trajan, and it was expanded to the inhabited area at the foot of the hill (Radt 2001: 50-1).

The Roman city extended westward beyond the western side of the Selinus River. The Asklepieion, one of the most famous healing sanctuaries in antiquity, was located 1 km west of the Roman city and 2 km west-southwest of the citadel, on the north bank of the Kaikos River. Founded in the fourth century B.C., it flourished especially in the Imperial Roman period when the Pergamene physician Galen was active as doctor for gladiators before he became the personal physician of Marcus Aurelius (Zschietzschmann 1955b: 1260).

The exact date of the abandonment of the city is unknown, though it seems to have existed at least until the third century A.D. A late Imperial fortification wall following the line of the Philetairean wall may indicate a significant decline in population size; alternatively the late wall may have been a temporary protection against raiding Goths in the middle of the third century A.D. In the Byzantine period many of the large buildings were torn down and quarried for building material. The acropolis was transformed into a mediaeval castle, a refuge for the inhabitants from Turkish invaders. After the city passed into possession of the Turks in the thirteenth century, the population was resettled in the southern plain “at the foot of the hill, where the modern city of Bergama is located” (Radt 2001: 53).

5.4 Communications

The valley of the Kaikos River allowed easy access to the Mediterranean Sea. The town of Elaea, on the Aegean Sea, served as harbor town for Pergamum. Toward the east, the Kaikos valley connected Pergamum with the Persian Royal Road leading from Kyzikos on the Black Sea to Sardis (Schäfer 1976: 688). To the south, a coastal road linked Pergamum, *via* Elaea, with Smyrna (Talbert 2000: 56).

5.5 Water Supply System

Since Pergamum was conceived as a fortress, the ability to withstand a prolonged siege was very important. In such an event it was necessary to supply the inhabitants with sufficient potable water. One natural spring was located in the Cetius valley (Fahlbusch 1982: 169). For the Hellenistic city, precisely due to its location high on a hill, wells and rain-fed cisterns were the only viable sources of water, in case natural sources in the lower areas were not accessible. Only one dug well was found in the lower agora. Hence the collection of rain water was the predominant method of securing the water supply in times of crisis. 80 cisterns were found in an area of only 8 ha on the acropolis of Pergamum. The density of cisterns was even higher on the medium levels of the city hill. By 1987, a total of 107 cisterns had been recorded by the excavators. The capacity of the cisterns ranged from 10-130 cubic meters (average 40-50 cubic meters). Most cisterns were located in private residences, but there appear also to have been public cisterns—the identification is not quite clear—in fountain houses along main streets. Except for two cylindrical cisterns with walls of masonry, all are bottle-shaped and were cut into the bedrock. The necks have round or square openings that were reinforced, if necessary, with a frame of stone. They were usually covered with a stone slab. Almost all cisterns had a waterproof lining of plaster on their interior surface. The filling usually occurred by means of ceramic pipes that collected rain water from surrounding roofs or, rarely, by means of channels collecting water from paved surfaces on ground level. Some cisterns were linked to one another by means of overflow orifices or tunneled openings. The consumers used jugs to draw water from the cisterns (Garbrecht 1987a: 17-8).

On the basis of an average density of 10-15 cisterns per hectare and an average volume of 45 cubic meters per cistern, assuming a minimum water requirement of 10 liters per *capita* per day, 25,000 people could have braved a one-year siege (Garbrecht 1987a: 18). Garbrecht does not specify clearly how the 10 liters per *capita* would have been used, but the amount of water was probably sufficient for drinking, food preparation, basic hygiene, and basic industrial processes and likely does not take into account requirements for watering livestock and for irrigation of gardens as sources of food for a prolonged period of time. An inscription found in the southeast part of the lower agora in 1901 gives evidence of the importance of the cisterns even at a period when the great Hellenistic and Roman aqueducts at Pergamum had been already in operation for centuries (Klaffenbach 1954; Garbrecht 1987a: 20). This so-called *astynomoi* inscription is a decree from the Trajanic period and reissues regulations that were in effect from the second century B.C. The *astynomoi* were city officials in charge of the administration and regulation of the city's infrastructure. In that capacity, these officials issued a decree that, among other items, required owners of private cisterns to keep those clean and in good repair. The inscription specifies fines for those individuals who do not follow the decree. When the decree was first issued, newly built aqueducts supplied the city with excellent continuously running water—a significant change in comparison with the stagnant water stored in the cisterns. The owners were presumably tempted to neglect the upkeep of the cisterns, which remained an important backup system in case of a cut to the supply of running water through warfare or natural disasters (Garbrecht 1987a: 20).

The aqueducts of Pergamum are among the best documented ancient water-supply systems of the Greco-Roman world. Modern research started with the rediscovery of the water-supply system by Carl Schuchardt in 1886 and was refined in 1896 by Carl Giebeler (Garbrecht and Holtorff 1973: 12-22). In 1968, Günther Garbrecht from the University of Braunschweig, in cooperation with the Middle East Technical University of Ankara, began a thorough survey of the remains. All recent research has been conducted by the engineers of the Leichtweiss-Institute for Hydraulic Engineering at the University of Braunschweig in Germany (Garbrecht and Holtorff 1973: 10-1). In their series *Mitteilungen des Leichtweiss-Institutes für Wasserbau*, over a period of 10 years seven contributions were published dealing with individual aqueducts that used to supply Pergamum in antiquity (Garbrecht and Holtorff 1973; Garbrecht and Fahlbusch 1975; Hecht 1975, 1977; Garbrecht 1978; Garbrecht and Fahlbusch 1978; Hecht 1983). The results are best summarized by Fahlbusch (1982) and Garbrecht (1987a). A total of 13 aqueducts of Hellenistic, Roman, Byzantine and Ottoman origin have been found and surveyed to date. During the Imperial Roman period, ten aqueducts were in operation simultaneously (Garbrecht 1987a: 22).

The first aqueduct was built under Attalos I (241-197 B.C.). Pipe stamps clearly identify him as the patron, therefore this line is known as the Attalos Aqueduct. The aqueduct consists of a single ceramic pipeline (segment length 0.55-0.63 m; internal diameter 0.13-0.14 m). The source was a natural spring at 800 m a.s.l., 12 km north of the city-hill. The pipe descended precipitously into the Selinus valley to an elevation of *ca.* 240 m a.s.l. From here it continued with a shallow gradient (0.3%) along the east face of the valley. The line crossed the depression north of the city-hill by means of an inverted siphon, combining stone and terracotta pipe elements, with a maximum pressure of some 25 m of water column. The end point was near the gymnasium complex of the Middle City at an elevation of 190 m a.s.l., presumably supplying the fountain. The volume flow rate should have been *ca.* 3 liters per second. The pipes of the Attalos Aqueduct, like those of the Demophon Aqueduct (see below), were buried in the ground on a bed of loam (Fahlbusch 1982: 169-70; Garbrecht 1987a: 23).

The second aqueduct was the so-called Demophon line, named, like the Attalos line, after its pipe stamps. It consisted of two parallel ceramic pipelines (segment length 0.54-0.59 m; internal diameter 0.175-0.19 m). The source of the Demophon line is unknown. It route becomes traceable only where it enters the Selinus valley. The Demophon line ran parallel to the Attalos line, but was built at a higher elevation. It crossed the depression north of the city-hill by means of an inverted siphon (*ca.* 30 m of water column), made of ceramic pipes. The gradient of the known sections of the

Demophon Aqueduct varied between 0.2 and 0.4%, and the volume flow rate may have been between 15 and 20 liters per second, depending on the elevation of the source. This line, too, probably supplied the gymnasia in the Middle City (Fahlbusch 1982: 170; Garbrecht 1987a: 24).

The Madradağ pipeline (Appendix: Fig. 0.9), the third aqueduct at Pergamum, was probably built under Eumenes II (197-159 B.C.). It had a total length of 42 km and consisted of three separate terracotta pipelines (segments 0.50-0.70 m; internal diameter 0.16-0.19 m; wall thickness 0.03-0.04 m) that were supplied by different springs located in the Madradağ Mountains, north of Pergamum (Garbrecht 1987a: 24). The pipelines were buried, like those of the two older aqueducts, just below ground level. The collecting reservoirs at the springs have disappeared, but ceramic shards indicate where the lines had their origin. The springs are located at 1,230 m a.s.l. (Aç Öldüren Suyu), 1,158 m a.s.l. (Koca Su), and *ca.* 645 m a.s.l. (Kemerdere). The second pipeline paralleled the course of the first after *ca.* 3 km; the third pipeline paralleled the course of the two after *ca.* another 13 km (Garbrecht and Holtorff 1973: 40 and figs. 3b and 4). The three pipelines then ran parallel until they reached the header tank (at 376 m a.s.l., Appendix: Fig. 0.10) on the southern slope of Mount Hagios Georgios, north of Pergamum and separated from the acropolis by a 200-m-deep valley. Apart from a tunnel 185 m long *ca.* half way along the triple line, no great engineering works were executed. The pipelines ran pragmatically at ground level always downhill for the entire distance. Different shapes of the pipe segments (some perfect cylinders, others with slight constrictions in the middle), different clay composition, and different pipe stamps indicate that at least four different shops delivered pipes for the project. The joints were caulked with an artificial combination of sand, silt, clay, and a mineral oil or wax ("Erdöl bzw. Erdwachs"). In contact with water, this mixture increases in volume by as much as 30 %, sealing efficiently the male-female joints (Garbrecht 1987a: 24). Experiments at the Middle East Technical University of Ankara conducted on a test rig of 22 original pipe segments from this aqueduct determined a pipe roughness coefficient of $\lambda=0.028$. The pipe length, head loss, and the roughness coefficient result in a theoretical volume flow rate of 15 liters per second per pipeline, or 45 liters per second for all three strands of pipeline combined. Allowing for a reduced discharge of spring water in summer, a realistic average flow rate over the year would be 30 liters per second (Garbrecht 1987a: 26).

The header tank on the slopes of Hagios Georgios was discovered in 1896 (Appendix: Fig. 0.10). It consisted of two adjacent chambers of equal size (3.62 x 1.21 m each). The three ceramic supply pipelines entered the northern chamber side by side through its short, northwestern wall at a height of 1.26 m above the tank floor. The two chambers were connected by three side-by-side openings (diameter 0.17 m) in the joint central wall, 1.15 m above the floor. The discharge pipe leading into the inverted siphon was located diagonally opposite the point of entry pipe in the south wall of the southern chamber. The header tank is located 35 m above the citadel of Pergamum, at a straight distance of 3 km (Garbrecht 1987a: 26). The pipeline of the inverted siphon was 3,450 m long (Garbrecht 1978: 4).

The lowest point of the inverted siphon is 193 m below the header tank (Garbrecht 1978: fig. 2)—a vertical distance that, once the pipeline was full of water, resulted in a static pressure of 18.9 bar in the pipes at the bottom of the valley. Since the pipes of the inverted siphon have disappeared, the question of their material had been debated for a long time. Terracotta, wood, or stone were already excluded as pipe material by the early twentieth century. The significant pressures at the bottom of the inverted siphon required the pipes to be of metal. Moreover, the total disappearance of all pipe remains strongly indicated that the material must have been a valuable commodity, *i.e.* metal. The two most likely possibilities were bronze or lead. Kootz (1963: 14) argued in favor of bronze as pipe material, citing precedents for large-scale availability and use of bronze. The outer shell of the Colossus of Rhodes, for example, was made of bronze in the third century B.C., indicating that bronze was available in large quantities and that the ancient craftsmen were very skilled in shaping it. A soil analysis that investigated the path of the pipeline for traces of copper, zinc, and lead showed a lead content 56 % above normal values. Therefore it is now certain that the pipe material was lead (Garbrecht 1978: 6-7; 1987a: 27).

The anchors that held the pipes in place are still visible. The anchors consisted of upright slabs of trachyte (1.20-1.50 m wide, 0.60-0.70 m high, 0.20-0.30 m thick) with a single central perforation (0.27-0.29 m diameter) that held the pipe (Appendix: Fig. 0.11). The distance between the slabs is between 0.92 m and 1.56 m. The top of most of the slabs is shattered because the valuable lead pipes were forcibly removed after the aqueduct had fallen out of use. Upstream of each upright slab rectangular cavities (0.4 m x 0.2 m) in the underground provided space for the joints between the individual pipe segments, perhaps some type of sleeve joint (Fahlbusch 1982: 70-1). Downstream of each upright slab, on the ground, were placed single horizontal slabs of roughly the same size as the uprights. Since the upper surface of the horizontals is level with the lower edge of the perforation, they must have been intended to provide added support to the pipe or to isolate it from the ground surface. Where the upright slabs rest on the bedrock, no horizontal slabs were placed, but the underground was worked down to be level with the perforation. Judging from the perforation in the upright slabs, the external diameter of the pipes must have been 0.30 m. The properties of lead do not require a large wall thickness even at an internal pressure as high as 20 bar.

The following procedure is used to determine the tensile stress in tangential direction in the wall of a pipe under pressure: the internal pressure p_i multiplied with the area formed by the internal pipe diameter d_i and a unit length l of pipe gives the force F that must be contained by the pipe wall.

$$F = p_i d_i l = 2\frac{N}{mm^2} * 220mm * 1mm = 440N$$

The pipe wall is subjected to a tensile stress σ_t that is equal to the force F generated by the internal pressure divided by the area formed by twice the wall thickness t and a unit length l of pipe.

$$\sigma_t = \frac{F}{2tl} = \frac{440N}{2 * 40mm * 1mm} = 5.5\frac{N}{mm^2}$$

The pipe wall will fail if the tensile stress σ_t in the wall exerted by the internal force F is equal or greater than the maximum tensile stress R_m= 10-20 $\frac{N}{mm^2}$ of the pipe material. Therefore, for a safe pipe:

$$\sigma_t \leq R_m$$

Garbrecht (1978: 7) states, incorrectly, as the above calculation shows, that the Madradağ pipeline has a safety factor of at least 13 for an assumed wall thickness of 0.04 m. My calculation shows a safety factor of 1.8-3.6. A wall thickness of 0.05 m has been suggested in a later publication (Garbrecht 1987a: 27), which would give a tensile stress of 4 $\frac{N}{mm^2}$ and a safety factor of 2.5-5. Fahlbusch (1982: 69-70) suggests a standardized thickness of 2 *daktyloi* (2 x 1/16 of a Philetairean Foot; 4.38 cm). A solid bar of metal this thick, even if it is as "soft" as lead, would be almost impossible to bend to a diameter of 0.30 m without causing the outside surface to tear lengthwise. Soldering the seam would also cause significant difficulty. Therefore it is most likely that the pipes were cast—a method that was used for the pipe of the inverted siphon at Aletrium (Fahlbusch 1982: 74). The inverted siphon must have consisted of *ca.* 2,500 pipe segments with an average length corresponding to the average distance between the upright perforated blocks (0.92-1.56 m). Each pipe segment may have weighed 4-5 kN (Fahlbusch 1982: 69) or 408-510 kg. Hence, the total weight of the lead pipeline used for the inverted siphon of the Madradağ aqueduct was 1,020-1,275 tons. In comparison, the lead pipelines of the four inverted siphons of the Gier aqueduct at Lyon (wall thickness 2.5 cm; 8-11 pipes in parallel; length of all four inverted siphons together 5,145 m) weighed 10,000 tons (Burdy 2002a: 157).

Asia Minor is particularly rich in deposits of *galena*, the mix of silver- and lead-ore (technically lead-sulfide and silver-sulfide). Forbes (1964: 214-15) lists 26 important deposits, three of which are located relatively close to Pergamum: ancient Ergasteria (*ca.* 75 km north, between Pergamum and Cyzicus); Mytilene, on the island of Lesbos (*ca.* 25 km by sea to the location of modern Dikili in Turkey, then another 25 km overland); modern Seferihisar, southwest of Smyrna (*ca.* 140 km). The cost of land transport, especially from the second location, to Pergamum would have been reasonable due to the relatively short distances involved. The cost of the lead itself is difficult to quantify.

Fahlbusch (1982: 79) states that in antiquity metals, including lead, were "*sehr teuer*" (very expensive). Relative transport costs for overland transport can be derived from Diocletian's Price Edict (A.D. 310), although, admittedly, the document is almost half a millennium later than the construction of the pressure pipeline at Pergmon. Nonetheless, the numbers quoted for transport costs establish a relative order of magnitude in comparison with the cost of day-to-day items. The Price Edict quotes a maximum allowed rate of 20 *denarii* per mile (*ca.* 1.48 km) for a wagon-load of 1,200 *librae* (*ca.* 392.4 kg or 0.3924 tons). 1,100 tons of lead would then be equivalent to *ca.* 2,800 wagon-loads that, in the time of Diocletian, would have cost a maximum total of 56,000 *denarii* per 1.48 km. The 75-km-stretch overland from Ergasteria to Pergamum would have cost *ca.* 2.8 million *denarii*, the 25-km-stretch from modern Dikili to Pergamum would have cost *ca.* 0.95 million *denarii* plus the sea transport from Mytilene, and the 140 km from Seferihisar to Pergamum would have cost 5.3 million *denarii*. These are overland transport costs alone. In comparison, the Roman Aqua Marcia was built in the mid-second century B.C. for an amount of 180 million sesterces or 45 million *denarii,* or little less than 0.5 million *denarii* per kilometer. The aqueduct at Aspendos was built in the second century A.D. with a private donation of 2 million *denarii*, but it is unlikely that this figure represents to the total cost of the aqueduct (Leveau 2001: 92-3). In comparison, from the same Price Edict, a farm laborer earned a maximum of 25 *denarii* per day and an advocate earned 1,000 *denarii* for pleading a case. A pair of high-quality boots cost a maximum of 120 *denarii*, a freight wagon was allowed to cost 6,000 *denarii*, and a *libra* (*ca.* 327 g) of gold was worth a maximum of 50,000 *denarii* (Humphrey, Oleson *et al.* 1998: 497; 503-5).

The inverted siphon of the Madradağ aqueduct is remarkable not only because of the enormous drop in elevation between header tank and valley bottom. Another interesting feature is that the designers have deliberately chosen to build the pipeline across the summits of two intervening hills, although it would have been shorter to follow the contour lines of the hills from Hagios Georgios to the acropolis. The pipeline descended from Hagios Georgios (368 m a.s.l.) to a shallow saddle (223 m a.s.l.), then rose to the first, or northern, intermediate hill (234 m a.s.l.). From here the line dropped to the lowest point of the valley (175 m a.s.l.), then rose again to the second, or southern, intermediate hill (235 m a.s.l.). From here the line dipped into the third saddle (193 m a.s.l.) and then ascended to the citadel, presumably to nearly 335 m (Garbrecht 1978: fig. 2). This arrangement makes the inverted siphon at Pergamum effectively an inverted triple siphon similar to the one in Aspendos. The high points at Pergamum, however, were not equipped with open basins, since they are located far below the line of the hydraulic gradient. Instead, the pipeline was held in place by enormous perforated stone blocks located on top of the hills (Garbrecht 1978: 4-5). The designers chose to build the pipelines straight across these interveneing hills in order to cross the topographic contour lines at right angles. Such an arrangement does away with the need to secure the pipeline against lateral displacement in case of frequently occurring earthquakes or landslides.

The exact location of the receiving tank on the acropolis is unknown. The anchor stones nearest to the citadel were found 20 m below the northeastern corner of the Arsenal. It is likely that the inverted siphon ended in the Royal Palace. Since the Palace was located at the highest point of the acropolis, the whole area of the citadel could have been supplied from here by gravity flow. Furthermore, the palace was a prestigious building, a worthy end point for a technological marvel such as this aqueduct. Outside of the city wall, on the line of the aqueduct, extensive foundations were found that may have been related to the aqueduct, but whose purpose is unclear to date. Finally, the largest cistern in the acropolis is located nearby and could have been filled with water from the aqueduct. The final ascent to the acropolis must have been vertical (Garbrecht 1987a: 27-8). Estimates of the total volume flow rate from the three feeder pipes into the header tank are in the range between 30 and 45 liters per second, or roughly 2,700–4,000 cubic meters per day (Garbrecht 1987a: 26). Assuming an internal pipe diameter of 0.20–0.22 m and a pipe roughness coefficient of $\lambda=0.025$ for the lead pipes, Garbrecht (1978: 7; 1987a: 27) restores the volume flow rate of the inverted siphon in the same range.

The late Hellenistic or early Roman Geyiklidağ aqueduct was discovered west of Pergamum in 1975/76. Pipe fragments indicate that the line consisted of a single strand of terracotta pipe. The individual segments were *ca.* 0.61 m long and had an internal diameter of 0.24–0.25 m. Ottoman and modern construction has to a large extent obliterated the remains of this aqueduct. It appears, though, that the Geyiklidağ aqueduct supplied the area of the Asklepieion with water (Fahlbusch 1982: 171; Garbrecht 1987a: 28).

Three parallel aqueducts ran south at different heights along the western slope of the Selinus valley. The Selinus “C” (double terracotta pipeline) and “D” (single terracotta pipeline) aqueducts are similar in construction to the Demophon aqueduct, and were, therefore, probably built in the early second century B.C. The end points of these two lines are unknown, but stamps reading “*APPOLONIOY*” and “*NAOY*” on some pipes of Selinus “C” indicate that these lines may have supplied the Nikephorion, a temple complex that was embellished under Eumenes II, but whose exact location is unknown. The third line, known as Selinus “E” (double terracotta pipeline), ran above the others, but its remains are extant *in situ* in only one location. A pipe stamp reading “*CAES*” indicates a Roman date for Selinus “E”. The origin of none of these three lines is known (Fahlbusch 1982: 171; Garbrecht 1987a: 30-1).

In the Roman period, the exact date is uncertain, the water from the three pipes of the Madradağ aqueduct was supplemented by a free-surface channel. The channel (0.50–0.55 m wide; 0.85–1.07 m deep) was covered by a barrel vault and, for the final two thirds of its course, ran parallel to the triple Hellenistic pipeline. Whether the channel emptied its water into the header tank on the slopes of Hagios Georgios is unknown. The tank was rebuilt and modified a number of times in antiquity. It is likely that at least part of the discharge of the Roman channel ran into the header tank, probably in order to even out the effects of annual variations in water supply from the three pipes. Another part of the discharge of the channel crossed the valley north of the city-hill across two arcaded bridges at an elevation of *ca.* 210 m a.s.l. that evened out the two deeper saddles formed by the intermediate hills. The northern bridge was significant in size (three tiers; height 30 m; length 700 m), the southern bridge was smaller (one tier; length 200 m). Since the Roman aqueduct was an open-channel conduit from beginning to end, it did not rise to the acropolis, but ended in the fountain at the level of the Demeter sanctuary in the Middle City (Fahlbusch 1982: 172; Garbrecht 1987a: 31-4).

The increase in population size during the Roman period necessitated the construction of another water-supply line. Since the Roman city was spread out primarily in the lower areas south and west of the city hill, it was possible to make use of the water from lower lying springs. The sources of the Kaikos aqueduct, built in the second century A.D., lay 34 km east of Pergamum near the ancient city of Germe (modern Soma). The line consisted of a vaulted open channel and had a total length of 53 km. The line was built by different gangs of workmen and, therefore, varies in width (0.85–1.10 m) and height (1.30–1.40 m) along its course. The channel maintained almost precisely a gradient of 0.031 % throughout its entire length. Compared to the aqueducts of the city of Rome, this gradient is very shallow (*e.g.*, Anio Novus 0.21 %, *i.e.*, 6.8 times steeper), and comparable to the famously shallow gradient of the aqueduct at Nîmes (0.035%). Sinter deposits on the channel walls indicate the depth of the flowing water and allow the volume flow rate of the channel to be determined to 200 liters per second. The line ended near Gurnellia, at the southwestern slope of the city hill, the possible location of a gymnasium from the Trajanic period (Radt 2001: fig. 2-6). If this assumption is true, it answers the question about both the date and the purpose of the Kaikos aqueduct: to supply the new Trajanic gymnasium with running water. The Kaikos aqueduct negotiated hills and valleys by means of 41 arcaded bridges and five tunnels between 100 and 1,650 m long. The biggest of the bridges, the Karkasos bridge, was 330 m long and 40 m high (*cf.* Pont du Gard: 262 m long; 48 m high) (Fahlbusch 1982: 172; Garbrecht 1987a: 35).

It is very likely that the slender bridges of the Kaikos aqueduct were damaged or destroyed in the severe earthquake of A.D. 178 that is recorded for the nearby city of Smyrna. The Aksu aqueduct took the place of the Kaikos line where the latter had been rendered dysfunctional. The Aksu line was joined to the Kaikos line 10 km west of Soma, and the branch from Soma to the junction was abandoned. A number of arcaded bridges of the Kaikos line were avoided by leading a new channel around the Mendese Deresi and the Karaskos valleys. Since the length of the line increased significantly due to these diversions, the local gradient was reduced to a mere 0.012 % over a distance of 14 km around the new channel loops (Fahlbusch 1982: 173; Garbrecht 1987a: 38-42). Even when the Roman channels were in operation at Pergamum, the Hellenistic inverted siphon was still the only means of long-distance water supply to the acropolis.

The volume flow rate of all ancient aqueducts of Pergamum taken together, 300 liters of water per second, or 25,000 cubic meters per day were entering the city. For a population size of 160,000 inhabitants, the discharge amounted to 160 liters per day and per *capita* (Fahlbusch 1982: 173). At Rome, in comparison, the Anio Novus alone, the largest of all aqueducts of the city of Rome, supplied between 1,470 and 1,850 liters per second.

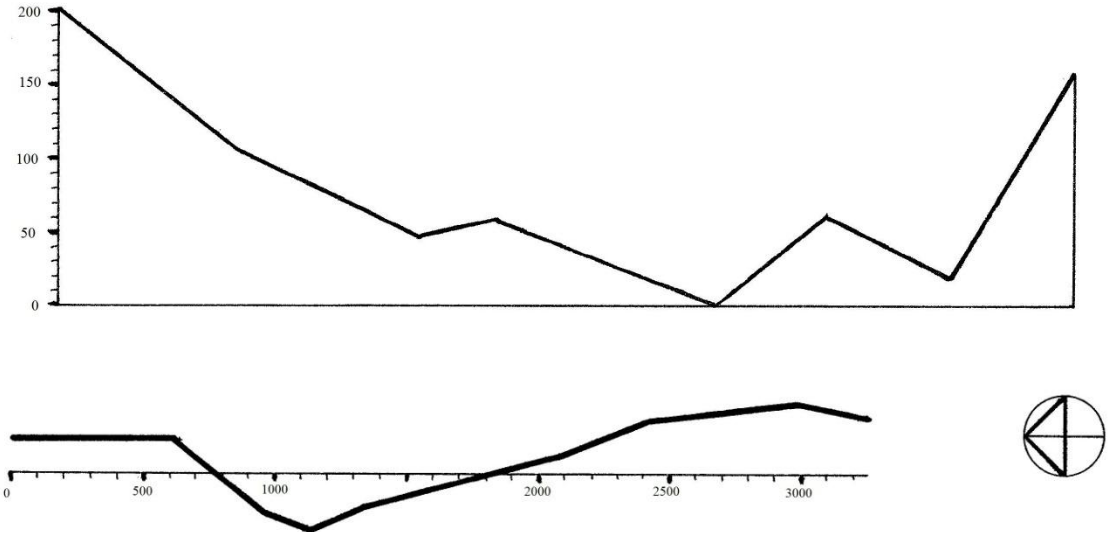

Figure 5.1: Evolved Elevation and Plan Pipeline Pergamum (Flow Direction Left to Right)

6. Smyrna

6.1 Location

The ancient city of Smyrna was located in western Turkey in the modern city of Izmir at 38°26′N latitude and 27°09′E longitude. The site lies at the Gulf of Smyrna (now called the Gulf of Izmir) on the Aegean Sea near the mouth of the Hermos River, which enters the gulf from the north. The gulf reaches 65 km inland and had, in antiquity, a width of 32 km. The coastline of the Gulf of Smyrna, especially the north coast, has changed significantly since antiquity due to alluvial deposits from the Hermos. To illustrate the amount of deposits: the Ottoman government decided in 1886 to regulate the course of the Hermos River mouth, otherwise the deposits would eventually have cut off the Gulf of Smyrna from the open sea (Bürchner 1955b: 735-36).

Another stream in the immediate vicinity of Smyrna, the Meles, originates east of the city and empties into the Gulf somewhere at the south-eastern tip. It is not clear today which of several small streams was known in antiquity as the Meles. The stream was mentioned numerous times in ancient literature, *e.g.* in the *Homeric Hymn* 9 (to Artemis). The river god Meles was famous because he was said to have been the father of Homer (Bürchner 1955b: 744).

6.2 Climate

Climate data for the city of Izmir is readily available from a number of sources. Bürchner (1955b: 737) gives an annual precipitation of 653 mm, averaged over the years 1858 to 1904. The value given by Weber (1900a: 5) is slightly lower: 610 mm averaged over the years 1864 to 1898. In comparison, the amount of precipitation for the city of

Athens as an average for the period from 1858 to 1904 was 393 mm (Bürchner 1955b: 737). Variation from year to year is very high. The wettest and the driest year respectively in the nineteenth century involved 1020 mm in 1874-75 and 165 mm in 1889-90 (Weber 1900a: 5-6). Over the course of a year, the distribution of precipitation is typically Mediterranean, with very dry summers (2-4 mm in July and August) and damp winters (108-131 mm in December and January).

More recent data derived from GHCN shows an annual average of 674.9 mm calculated over 1175 months between 1864 and 1989. This number is slightly higher than the values given by Weber and Bürchner, but all three mean values vary only ± 10% from one another.

Precipitation Data, average 1864 – 1898: (Weber 1900a: 5)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	108	75.1	70	43	29	14	4.3	2.4	19.8	50	83	111.4	610

Precipitation Data, average 1858 – 1904: (Bürchner 1955b: 737)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	110	84	81	43	32	14	3	2	18	44	91	131	653

Precipitation Data, average 1864 – 1989 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	126.9	94.5	76.3	41.7	32.1	9.8	2.8	2.8	15.6	45.2	87.7	135.3	674.9

Temperature data for the city of Izmir is also available from GHCN 1. The numbers are obtained from data gathered over 1070 months between 1843 and 1988. The distribution is again typically Mediterranean with hot summers (July and August above 25 °C, May through September above 20 °C).

Temperature Data, average 1843 – 1988 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	8.0	8.8	11.0	15.1	20.1	24.4	27.1	26.6	22.8	18.3	13.7	9.9	17.1

It follows that in the long-term average for Smyrna the months from May to September must be considered arid.

6.3 Topography

It is necessary to distinguish between Old Smyrna (*Palaia Smyrna*), a city inhabited from the Late Bronze Age until its destruction by Alyattes around 600 B.C., and Hellenistic and Roman Smyrna, founded by Alexander the Great, roughly four kilometers further to the south. Old Smyrna was located at the north-eastern tip of the Gulf of Smyrna in present day Bayraklı. The Hellenistic settlement was founded on Mount Pagos, located in modern Izmir proper, from where it soon expanded towards the northwest, surrounding the harbor in the Roman period and bounded by the Gulf of Smyrna to the north and west. Because of 2,300 years of continuous habitation, construction, migration, and modernization (Appendix: Fig. 0.12), it is nearly impossible to reconstruct today the layout of the ancient city (Bürchner 1955b: 746).

The citadel of Smyrna is located on Mount Pagos at an elevation of 183 m a.s.l. (Weber 1900a: pl. 3). Pausanias (7.5) mentioned the name *Pagos*, while Pliny the Elder (5.118) called the hill *Mastusia*. In antiquity, the lower city spread out between Mount Pagos and the Gulf of Smyrna, roughly 2.5 km wide and 6-7 km long. The slope of Mount Pagos drops sharply to the east to an adjacent streambed that runs in a northerly direction at a height of 25 m a.s.l. Weber (1900a: pl. 2) assumed that this stream was the Meles. In fact it is called Melez in Turkish today. The Barrington Atlas (Talbert 2000:

56), however, labels this stream as Kaleon, and shows the Meles flowing further to the north into the Gulf of Smyrna from the east instead. East of this stream the ground rises sharply again towards the Nif Dağ or Olympos Mountains, as they were called in antiquity, to a height of 1500 m a.s.l. at a distance of 20 km east of Mount Pagos (Bürchner 1955b: 749).

6.4 Communications

A road to Sardis led from Smyrna 85 km east through a valley between the Olympos Mountains to the south and Mount Sipylos (present day Yamanlar Dağ) to the north. Another road ran 75 km south to Ephesos. Pergamum is located 90 km north of Smyrna along a coastal road that turns inland at Elaea (Talbert 2000: 56).

The Gulf of Smyrna offers excellent anchorage for seagoing ships. The location of the city harbor in the south-east corner of the Gulf offered a well-protected, crescent-shaped setting. Therefore the location of the city is ideal for communication between the Mediterranean Sea and Sardis to the east, as well as along the road from Pergamum to Ephesos.

6.5 History

The history of the Ionian city of Smyrna goes back to the first half of the third millennium BC. Strata from the second millennium B.C. are contemporary and show close relations with the Hittite civilization (Akurgal 1990: 119). The foundation myth recorded by Strabo (14.1.4) relates that the first city was founded by an Amazon called Smyrna. According to Bürchner (1955b: 745) the myth indicates that the ancient Greeks were well aware of the barbarian origins of the city. Recent excavations in the area of

Izmir put the date of the first confirmed settlement into the Late Neolithic period (Çilingiroglu, Derin *et al*. 2004: 3).

The site of the prehistoric to archaic settlement *Palaia Smyrna* lies, according to Strabo (14.1.37), twenty stades (roughly 4 km) north of the Hellenistic and Roman city in present day Bayraklı (Akurgal 1990: 119). Archaic Smyrna is most famous for the Temple of Athena with its terraced *temenos* (580 B.C.). The late seventh and early sixth centuries B.C. were the most prosperous period for the city. Houses of this period were commonly of the *megaron* type. Their north-south orientation suggests axial grid planning of the city (Akurgal 1976: 847). The Archaic city was destroyed around 600 B.C. by Alyattes (Bürchner 1955b: 745). After the destruction, the survivors were forced to live in villages (*Strabo* 14.1.37). The inhabitants gradually returned to the city, but the settlement became insignificant in the fifth and fourth centuries. It was subsequently abandoned completely in favour of the new site (Akurgal 1990: 121).

The Hellenistic city was founded by Alexander the Great and built by Antigonos Monophthalmos (382-301 B.C.) (Bürchner 1955b: 748). Pausanias (7.5) related the legend of a vision in which the Nemeses appeared to Alexander in his sleep:

> The modern city was founded by Alexander, the son of Philip, in accordance with a vision in a dream.
>
> It is said that Alexander was hunting on Mount Pagus, and that after the hunt was over he came to a sanctuary of the Nemeses, and found there a spring and a plane-tree growing over the water in front of the sanctuary. While he slept under the

> plane-tree it is said that the Nemeses appeared and bade him found a city there and to remove into it the Smyrnaeans from the old city.
>
> So the Smyrnaeans sent ambassadors to Clarus to make inquiries about the circumstance, and the god made answer:—”Thrice, yes, four times blest will those men be who shall dwell in Pagus beyond the sacred Meles.”
>
> So they migrated of their own free will, and believe now in two Nemeses instead of one, saying that their mother is Night, while the Athenians say that the father of the goddess in Rhamnus is Ocean. (trans. adapted from W.H.S. Jones)

The new city was therefore founded on the slopes of Mount Pagos. This legend was depicted on coins issued at the time of Marcus Aurelius, Gordianus, and Philip the Arab (Akurgal 1990: 121). The precise location of the Hellenistic and Roman city of Smyrna is known from numerous milestones, found *in situ*, that show distances to the city (*e.g. CIL* III 471, 472, 474, 476). The elliptical citadel was enclosed in a wall of 1,730 m length. The long axis of the enclosed area was 458 m long (Bürchner 1955b: 752).

In the Augustan period, Strabo (14.1.37) called Smyrna the “most beautiful city in Ionia.” At that time the city had extended from Mt. Pagos towards the flat land around the harbour. He wrote further:

> One portion of Smyrna is built up on a hill, but the greater part is in the plain near the harbour, the Metroum, and the Gymnasium. The division of the streets is

> excellent, and as nearly as possible in straight lines. There are paved roads, large quadrangular porticos, both on a level with the ground and with an upper story.
>
> There is also a library, and the Homereium, a quadrangular portico, which has a temple of Homer and a statue. For the Smyrnæans, above all others, urge the claims of their city to be the birth-place of Homer, and they have a sort of brass money, called Homereium. (trans. H. C. Hamilton and W. Falconer)

According to Strabo (14.1.37), the only drawback was the lack of drainage. Aelius Aristeides (*Orationes* 17.11 K), too, praised the straight and well-paved streets of the city as well as the fact that the east-west orientation of the main thoroughfares allows the wind from the sea to cool the city (Akurgal 1976: 848).

There are no estimates of the population size of Hellenistic or Roman Smyrna. Smyrna suffered serious damage from an earthquake in A.D. 178. Damaged public buildings were reconstructed with help from Marcus Aurelius (Akurgal 1976: 848).

6.6 Water Supply

A total of six aqueducts were built to supply the city of Smyrna/Izmir between the Hellenistic period and the seventeenth century. The primary publication on the water-supply systems at Smyrna is more than a century old (Weber 1900a). As the modern city of Izmir (with a population of roughly 3 millions) has spread above the remains of ancient Smyrna, the vestiges that were still visible in the late nineteenth century have today vanished. It is, therefore, unlikely that many new finds will come to light in the future to add to Weber's information. He described the remains of all six aqueducts, two or three of which he dates to antiquity. The others were built in the Byzantine to Turkish periods.

It is unknown how the citadel of Smyrna was supplied with water before the construction of the aqueducts. Weber (1900a: 183) described six reservoirs, which he called rain caskets (“Regensärge”). They were oblong rectangular tanks sunk into the underground, each covered with a barrel vault. Their walls were built of irregular stones with a lining of plaster 1-2 cm thick. The corners of the reservoirs were rounded. The vaults had collapsed at the time of Weber’s visit. The reservoirs were of various sizes, the largest one 10.5 x 3.8 m, divided by a wall into two chambers. The smallest one was 3 x 2 m. Weber (1900a: 184) gave the depth of only the shallowest reservoir: 0.6 m. It is unknown if the reservoirs were built before or after the construction of the aqueduct. A very large cistern of 33 x 23 m with a vault held up by 20 pillars and a depth of 5.2 m probably dated to the thirteenth century A.D. (Weber 1900a: 185).

A gravity-fed aqueduct could bring water to the citadel of Smyrna only from areas higher than the elevation of Mount Pagos (183 m a.s.l.). Mount Pagos drops steeply to nearly sea level on the north, east, and south. To the southwest the descent is smoother, towards a range of hills approximately 100 m a.s.l. Rain water runs off very quickly on the volcanic trachyte rock that makes up Mount Pagos (Weber 1900a: 5). Water collection and storage with cisterns was an unreliable strategy due to the strong variation of rainfall over the year and from year to year (see above). Weber (1900a: 6) reported a large number (“grosse Zahl”) of Turkish wells on the citadel, but suggested that they were bound to dry up over the summer. The trachyte of Mount Pagos was cleft in many places and was able to capture and store a certain, yet insufficient quantity of rain water over the winter. Therefore, it was necessary to bring in water from elsewhere. The immediate surroundings of Mount Pagos are either not high enough to build a gravity-fed aqueduct for the supply of the citadel, or, where they have the necessary elevation, there are no suitable springs (Weber 1900a: 6). The only viable solution was to bring in water from the higher elevations of the Nif Dağı Mountains (ancient Mount Olympos), 18 km east of the city.

A spring called Karapınar ("black spring", spelled Kara-Bunar by Weber before Atatürk's introduction of Latin script in Turkey, and Kara-Púnar by Bürchner) is located at an elevation of 750 m a.s.l. on the west slope of the Mountains, 13 km east of Smyrna (Weber 1900a: 7 and pl. 2), approximately at 38º26' N, 27º17' E. The Karapınar aqueduct brought water from this spring to the citadel at Smyrna. It included a pressurized pipeline that crossed three intermediate high points on its route from the source to the citadel of Smyrna. Due to its similarities with the Madradağ aqueduct at Pergamum, the Karapınar aqueduct may have been built in the Hellenistic period by Pergamene engineers (Lewis 1999: 161). Hodge (1992: 33), in contrast, states that due to the general difficulties in dating ancient water supply systems the Karapınar aqueduct could also be an early Roman structure.

Numerous fragments of terracotta and stone pipes were built into field walls, farmers' huts, and houses along the probable course of the aqueduct. Many of the stone pipe fragments consisted of red trachyte of the type used to anchor the Madradağ-Pipeline at Pergamum on top of its intermediate hill (Garbrecht 1978), and which Lewis (1999: 169) believes is the *saxum rubrum* that Vitruvius (*De architectura* 8.6) recommended as material for *geniculi* in the section on pressurized water pipelines. Weber (1900a: 21) counted more than sixty complete or fragmented pieces of stone pipe.

The source of the Karapınar line consisted of three springs whose water was diverted by a dam to the entrance of the aqueduct. Weber found well worked ("gut behauene") quadrangular stone blocks from the dam that still lay loosely on top of one another. In Weber's (1900a: 22) judgment the water was excellent, and the best in all the environs of Smyrna. As mentioned above, the springs were located at an elevation of 750 m a.s.l. in the Nif Dağı Mountains, roughly 13 km east of the Pagos, the hill on and around which the Hellenistic city was built. Weber's map (1900a: pl. 2) shows that the total aqueduct length from source to city was roughly 24 km. Weber's description of the aqueduct from the source to the beginning of the inverted siphon is relatively vague, although this stretch is by far the longer portion of the line—approximately 20 km. This imprecision is illustrated by the fact that Weber (1900a: 21) gave distances in "hours traveled". The remains that Weber was able to observe along this long initial stretch of the aqueduct were rather tenuous and limited to certain points here and there. The terrain consisted of limestone, which is prone to erosion. Frequent earthquakes and winter runoff had altered the topography and largely obliterated the aqueduct (Weber 1900a: 22).

Close to the source at an elevation of 660 m a.s.l. the ancient designers had to cut through a wall of rock to allow the aqueduct to pass through in southwesterly direction. The cut was 8 m wide and 4-5 m deep, and was known in Weber's time as *portara*, or "large gate". Weber (1900a: 22) recorded a 10 m stretch of channel cut into the bedrock at this point. The channel itself was 0.6 m deep and 0.5 m wide. Where the aqueduct was preserved, it consisted of a masonry channel 0.42 m wide with a cement finish on the internal surfaces. Weber found long stretches of the channel, in places covered with stone blocks, at an elevation of 530 m a.s.l.

At an elevation of 360 m, Weber found an 8 m stretch of terracotta pipeline *in situ* on the ground. The individual pipe segments were 0.45 m long with an internal diameter of 0.23 m and a wall thickness of 4.5 cm. Weber (1900a: 21) did not comment on the relation of this stretch of pipeline to the aqueduct, but the design and dimensions of the pipes would be appropriate to assume that they belonged to the same structure.

The aqueduct negotiated in a terracotta pipe eight depressions by following the contour lines, which implies that the water ran with a free surface through the pipe. Individual pipe segments, reused by local farmers in huts and houses as flues, were 0.45 m long with an internal diameter of 0.21 m and a wall thickness of 6 cm (Weber 1900a: 23). Weber followed the numerous terracotta pipe fragments down to Point A on the map (Weber 1900a: pl. 3). Point A lies at an elevation of 188 m, five meters higher than the citadel on Mount Pagos. As the following course of the aqueduct ran steeply downhill, crossing the contour lines at right angles, it is likely that the inverted siphon began at this point. Weber, however, was unable to find traces of a header tank (Weber 1900a: 24).

Weber (1900a: 8-21) described in detail the final section of the aqueduct east of the citadel of Hellenistic Smyrna. The easternmost remains of this stretch were two pieces of wall at an elevation of 166 m a.s.l., east of the upper road to Buca (“obere Strasse nach Budscha”), Point B on his map (Weber 1900a: pl. 3). The larger piece of wall was 3 m in length, 4.5 m high, and 2 m wide, made of mortared rubble, faced with roughly cut quadrangular blocks (Weber 1900a: 8). The smaller piece was located at a distance of 7 m from the larger one. It was 5 m in length, lower than the other one (Weber gave no height), and also 2 m wide. The two pieces were not exactly in line, but were shifted sideways from each other by 2 m.

No more traces of wall were visible towards the upper road to Buca until 54 m east of the road, where it reappeared in faint traces again. West of the road, wall remains up to 4.5 m high were visible, running west for a distance of 115 m. The road was at an elevation of 142 m a.s.l. The aqueduct crossed it at this point by means of an arcaded bridge. The terrain rises toward the west to a first intermediate hill at 161 m a.s.l. Where the terrain rises, the wall remains disappeared. At Point C, 50 m east of the intermediate high point, Weber found the first fragment of a stone pipe built into a field wall, and more fragments reused in little huts scattered along the southern slope of the intermediate hill (Weber 1900a: 9). The stone pipe segments were D-shaped in cross-section, on average 0.5 m high and about as wide and long, manufactured from red trachyte. The internal diameter of the circular bore was 0.13-0.18 m, and the individual pipe segments must have been joined directly to one another by means of male-female joints. Weber was unable to ascertain whether or not there had been a tower on the intermediate hill. He found an overgrown heap of stones ("wüsten Steinhaufen"). He furthermore reported abundant fragments of ancient terracotta pipes (Weber 1900a: 10).

No more remains of a wall were visible further west, down the slope of the intermediate hill, but more stone pipe fragments reused in field walls indicated that the pipeline had continued in this direction. Weber gave the internal diameter of one of these fragments as 0.24 m and an external block width of 0.7 m (Weber 1900a: 10).

Further west, the aqueduct crossed a second intermediate high point (“Teressi”, at 136.6 m a.s.l.). The saddle between the first and second high points is not very pronounced. On this second high point Weber found the decayed remains of a chamber, which he calls tower (“Thurm”) for lack of a better term, built of mortared rubble (Weber 1900a: 11). He found no trace of hydraulic cement. In the northwest corner of the quadrangular chamber in the wall, at a height of 1.36 m above the floor, he found a terracotta pipe *in situ* with an internal diameter of 0.24 m. More stone pipe fragments littered the surrounding area. One of these had a funnel-shaped opening in its side wall very similar to specimen found in Laodicea (Weber 1898: 1).

At this point the aqueduct crossed the lower road (“untere Strasse”) to Buca that ran through a saddle at 88 m a.s.l. This saddle is more pronounced than the one through which the upper road ran. Since the lower road was more frequented than the upper one, the arcaded crossing (“Karakapi”) was larger here. Weber was unable to determine the width of the gate from the remains, as the wall east of the road was completely torn down, and survived up to a height of 4.8 m west of the road. The gate must have been largely intact at the beginning of the nineteenth century (Weber 1900a: 13).

Near this point, Weber found fragments of terracotta and stone pipes. The stone pipe fragments were again D-shaped in cross-section and of similar size as those described above, with sinter build-up in the bore. One of the terracotta pipes had a wall thickness of 0.09 m and an internal diameter of 0.13 m. The male end of the adjacent pipe was still *in situ* in the female end of this pipe and was firmly held in place by a very firm joint of lime mortar (“Kalkverbindung”). Two more terracotta pipes found nearby had a slightly larger bore and thinner wall thickness (Weber 1900a: 14).

Further west, the traces of the wall disappeared. Pipe fragments were visible in modern field walls nearby, as was one terracotta pipe on the ground and another used as a chimney on a nearby hut. The terracotta pipe on the ground had a bore of 0.2 m and a wall thickness of 0.06 m (Weber 1900a: 15).

The line reached another high point before it dropped precipitously to cross a stream that Weber identified as the Meles. This high point consisted of “wildly cleft rock” (“wild zerrissenen Felsen”) at an elevation of 112 m. Although no remains of the line were visible at this point, it is likely that the line bypassed this broken rock to the south, so that the actual high point in the aqueduct was 106 m, the elevation at which Weber found the last stone pipe before the drop. At point D (Weber 1900a: pl. 3), a cut channel 1.45 m wide and 9.3 m long must have served to hold the stone pipeline in place as it descended the steep slope towards the stream (Weber 1900a: 15).

The wall reappeared at the bottom of the slope by the railway line east of the streambed, parallel to it, and 20 m above it. Seven stone pipes corresponding to those previously described had been found at this point during construction of the railroad (Weber 1900a:15). The width of the D-shaped segments was 0.52 m with a length varying between 0.48 m and 0.56 m, a height between 0.51 m and 0.53 m. The bore was 0.22 m. They were joined by means of male-female joints sealed with lime mortar. Some of the stone pipes have fragments of terracotta pipe stuck in their joints, so that the stone pipes were not necessarily joined directly to each other, but to terracotta pipes, as was the case at Ephesos (Forchheimer 1923). The aqueduct crossed the stream on a two-arched bridge, little of which has remained. The ancient bridge-heads held a wooden bridge in Weber’s time. The stream bed is at an elevation of 25 m (Weber 1900a: 17; pl. 3).

The remains of the wall reappeared on the western side of the stream and ran straight up the slope until they reached the later Osman Ağa aqueduct at an elevation of 55.5 m. At this point Weber found twelve well-preserved stone pipe segments reused in various modern buildings. Among these was a nearly cubic segment (side lengths 0.61 m, 0.65m, and 0.69 m). The bore had a 90° bend in one plane, and another 90° bend in another plane, *i.e.* a cube with three orifices on three sides. The bore of two of the orifices was 0.3 m. The third and smaller of the orifices consisted of a terracotta pipe. Weber (1900a: 18) did not give the diameter of the pipe, nor did he venture a guess regarding the purpose of this block. He stated: “I leave the interpretation of this block to the expert.” (“Die Erklärung dieses Blockes überlasse ich dem Fachmann.”)

Here the aqueduct turned north. In the previous course the designers took care to cross the topographical contour lines at right angles. Now for a stretch of more than one kilometer it is conjectured that the line ran uphill at an angle of 10° to 20° to the contour lines, making it vulnerable to erosion and landslides. The terrain was very rocky and broken up, and Weber was not able to find traces of a wall. The presence of stone pipe segments at the top of the slope on a saddle west of the city wall indicated where the aqueduct reached the height near the citadel (Weber 1900a: 19).

It is unknown if the aqueduct entered the citadel proper, and how, since all hydraulic installations within the citadel date to the Byzantine period. A D-shaped stone pipe segment was reused in the SE-corner of the Byzantine citadel wall, which indicates that at the time of construction of this wall the aqueduct may have been out of use (Weber 1900a: 19-20).

Weber was able to find four more stone pipe segments on the northern slope of the Pagos, two of which again contained three orifices, as the block described previously. One of the segments was larger than the other three and had no male or female joints. It is, therefore, unclear whether it belonged to the aqueduct in question (Weber 1900a: 20).

The local population used to quarry the aqueduct for building material. Weber found eleven more stone pipe segments reused in modern buildings. In size and shape they corresponded to the stones found near and on the aqueduct line. According to the local inhabitants most stones had been brought from Karakapı, where the aqueduct crossed the lower road to Buca. In one of the quadrangular stone blocks two parallel bores in one face joined into one and turned 90° to form one bore on the adjacent face of the block. Weber (1900a: 21) doubted that this block belonged to the Karapınar aqueduct.

The inverted siphon of the Karapınar aqueduct crossed a depression 154 m deep, *i.e.* the height difference between the lowest point of the Meles (25 m a.s.l. + 5 m bridge height) and the top of the citadel (184 m a.s.l.). This assessment is not quite correct, as a header tank or an entry point into the inverted siphon at or near Point A (188 m a.s.l.) (Weber 1900a: 25) would have been higher than the citadel. Hence the drop would have been at least 158 m, assuming that Point A was the lowest possible starting point for the inverted siphon.

Same as the Madradağ pipeline at Pergamum, the designers of the Karapınar pipeline chose to build the pipelines straight across these interveneing hills in order to cross the topographic contour lines at right angles. Such an arrangement does away with the need to secure the pipeline against lateral displacement in case of frequently occurring earthquakes or landslides.

The Akpınar (=white spring) Aqueduct was the second line that Weber clearly ascribed to antiquity. For this investigation it is of only minor relevance. The Akpınar spring was located 17 km south of Smyrna at an elevation of 130 m a.s.l. A domed fountain house covered the spring, and the water was initially collected in a small pond (Weber 1900a: 168). The aqueduct brought the water in an open channel, within the city in a terracotta pipeline, to a hill west of Smyrna, now called Deirmen Tepe. Two inscriptions from the Roman period (*CIG* 3146 and 3147) indicate that it ended in or near the Temple of Zeus Akraios (Bürchner 1955b: 754-55). The aqueduct dates to *ca.* A.D. 62 (Bürchner 1955b: 754). It was built partly underground, partly on bridges and ended in a basin (diameter 1 m), built into a wall from where it flowed into the Temple of Zeus (Weber 1900a: 174). There are no estimates of the volume flow rates of either of these aqueducts.

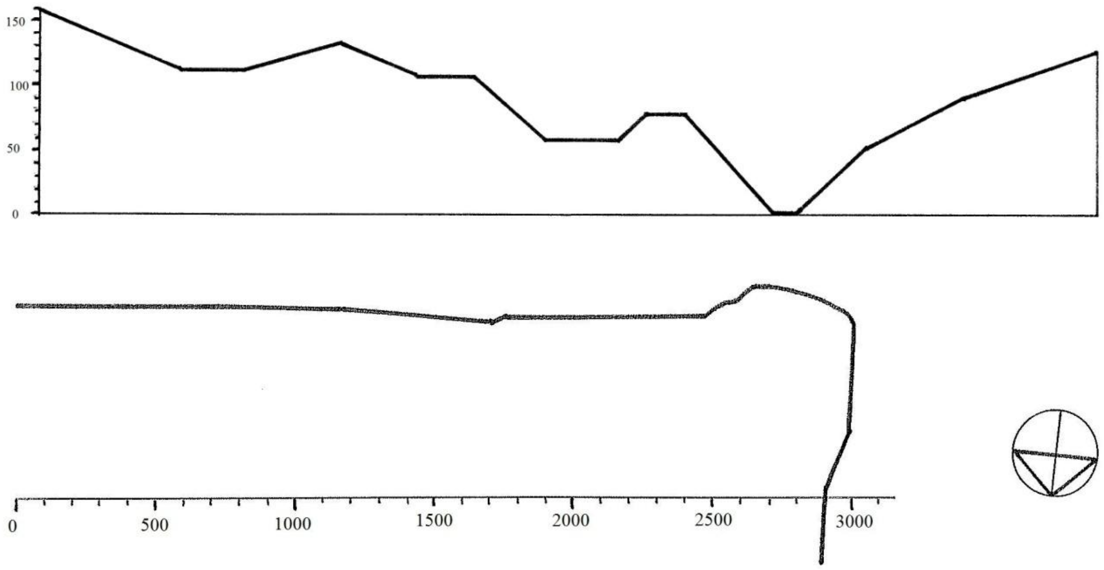

Figure 6.1: Evolved Elevation and Plan Pipeline Smyrna (Flow Direction Left to Right)

7. Methymna

7.1 Location

The site of ancient Methymna is located at 39°22′ N latitude and 26°10′ E longitude, 61 km northwest of Mytilene, on the north coast of the island of Lesbos. The island has a surface area of 1,630 square kilometers and is located 12 km off the west coast of the Turkish mainland (ancient Aiolis). The east-west running northern coastline of Lesbos forms a 90°-angle towards the south with Methymna at the apex. A promontory, Dabia, protrudes westward from the apex and forms a roughly quadrilateral piece of land, with side lengths of *ca.* 800 x 800 m. Methymna is located west of Mount Lepetymnos, a mountain that reaches a maximum height of 893 m a.s.l. The official name of the modern city is transliterated Mithymna (from Greek Μήθυμνα), but the city is known today also as Molyvos or Molivos, the name it had under the Ottoman Empire. The exact location of ancient Methymna is known from Strabo (13.2-3) and from epigraphic evidence. The classical city was built at an elevation of 93 m a.s.l., on a steep hill that is crowned today by the remains of a mediaeval Genoese fortress. (Bürchner 1955a: 2111; 1955a: 1392). Methymna is the mythological birthplace of Arion, the inventor of the dithyramb (Herodotus 1.23).

7.2 Climate

Data for average temperatures at the weather station at Mytilene, located at the east coast of Lesbos, at 17 m a.s.l., are derived from GHCN 1 over a period of 118 months between 1981 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	9.4	9.1	11.2	15.6	19.3	23.7	25.8	25.4	22.9	17.8	13.0	10.9	17.1

The station at Mytilene does not provide any precipitation data. The weather station at Izmir is located sufficiently close and in a sufficiently similar geographical setting to make it probable that the average precipitation at Mytilene is similar to that at Smyrna. The data for Izmir, derived from GHCN 1 (Hoare 2006), show an annual average of 674.9 mm calculated over 1175 months between 1864 and 1989.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	126.9	94.5	76.3	41.7	32.1	9.8	2.8	2.8	15.6	45.2	87.7	135.3	674.9

For comparison, precipitation data are available also for the Turkish station of Çanakkale, near the ancient site of Troy, at the south entrance to the Dardanelles, 90 km north-northwest of Methymna. The weather station at Çanakkale lies at 3 m a.s.l., and the data are derived from GHCN 1 for 475 months between 1951 and 1990 (Hoare 2006).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	106.7	69.4	67.4	45.7	31.6	22.5	12.9	7.5	25.1	49.1	90.9	106.1	635.2

The precipitation data for Çanakkale show overall a slightly drier climate than at Izmir (635.2 mm *vs.* 674.9 mm). More precipitation falls in Çanakkale in summer (*e.g.* July, 12.9 mm, *vs.* 2.8 mm in Izmir), but Izmir has wetter winters (*e.g.* December, 106.1 mm in Çanakkale, *vs.* 135.3 mm in Izmir), while the respective values in spring and in autumn are almost identical (*e.g.* May, 31.6 mm in Çanakkale, *vs.* 32.1 mm in Izmir). It is hard to judge, which of these two stations better reflects the situation at Methymna. The overall difference between the two, however, is rather small, and within the framework of this investigation, either of the two data sets will yield the same conclusion: the climate at Methymna is typical of the Mediterranean region with hot, dry summers and cool, damp winters. It follows that at Methymna the months of May through September must be considered arid.

7.3 History

Methymna was one of five Aiolian settlements on the island (together with Mytilene, Antissa, Eresos, and Pyrrha), and was the second most powerful city after Mytilene (Zschietzschmann 1955a: 1391). A prehistoric settlement, known today as *Palaia Methymna*, existed in a small (roughly 5 ha), low-lying plain on the north coast of Lesbos, 1 km north of the city-hill (Appendix: Fig. 0.14). Evidence for human occupation in this area goes back to the third millennium B.C. (Buchholz 1976: 121). An Archaic settlement grew, judging from remains of Archaic city walls, at Dabia-West, north and northeast of the modern harbor. It is unknown whether the Archaic settlement replaced the one at *Palaia Methymna*, or if they existed side by side for some time (Buchholz 1976: 137).

Myrsilos of Methymna mentions the founding by Methymna of the colony of Assos in modern Turkey. The earliest archaeological evidence at Assos dates to the late eighth century B.C., which means that at that early date Methymna was capable of planning and executing large-scale overseas projects (Buchholz 1976: 138). Herodotus

(1.151) writes about the conquest of the neighboring city of Arisba by Methymnaeans. The event can be dated probably to the late seventh century B.C. The take-over of the territory of Arisba placed Methymna in close competition with Mytilene for preeminence on the island of Lesbos (Buchholz 1976: 139).

Fragments of Attic red-figure ceramics and others with black slip found on the acropolis show that the city-hill must have been inhabited in the fifth and fourth centuries B.C. Archaic grey ware typical of Dabia-West, however, is entirely absent from the archaeological record in the acropolis. It is likely, therefore, that the city-hill was occupied and built over only in the fifth century B.C. (Buchholz 1976: 44). The inclusion of the easily defensible city-hill around the early fifth century can be linked to the Ionian revolt and the subsequent punitive expedition of the Persians against the island of Lesbos in 493 B.C. (Herodotus 6, 31).

During the Peloponnesian War, Methymna hoped to gain an advantage over Mytilene by supporting Athenian interests on the island of Lesbos. Methymna did not support the Lesbian revolt against Athens in 428 B.C., and hence did not suffer from subsequent Athenian punitive measures (Thucydides 3.2; 3.50). In the spring of 406 B.C., a Spartan fleet besieged and took Methymna, likely through treason. The Spartans returned the city to the Methymnaeans, but remained in control of Lesbos (Diodorus 13.76). In 386 B.C., Sparta withdrew from Lesbos under the provisions of the King's Peace, and Methymna possibly entered into an alliance with Athens. In 378/7 B.C., Methymna joined the Second Athenian League. Not much is known about the city in the mid-fourth century B.C. (Buchholz 1976: 147).

Only few details about events in Methymna after Alexander's death are known. In 302 B.C., Prepelaos conquered the island of Lesbos on behalf of Lysimachos. After the Battle of Ipsos, in 301 B.C., Lesbos—like Pergamum—fell to Lysimachos, before it came for two generations under the control of the Ptolemies. With the decline of the Ptolemaic power after 190 B.C., the city came under the influence of the Attalids. In 167 B.C., the city of Antissa was destroyed by the Romans for granting safe haven to ships of Perseus of Macedonia. The inhabitants of Antissa were relocated to Methymna, which brought about the expansion of the city to Dabia-East. In the middle of the second century B.C., Methymna was involved in the conflict between Prusias II of Bithynia and Attalos II of Pergamum. Prusias devastated the territory of Methymna and in 155 B.C. was forced by the Roman senate, which had significant influence on the peace accord, to pay an indemnity to the city. Methymna was a steadfast ally of Rome in the fight against Antiochos III and entered into a formal alliance with Rome in 129 B.C., the year in which Rome established the province of Asia. During the first century B.C. and through the Roman Imperial period, interest in the island of Lesbos focused primarily on Mytilene. There is almost no mention of Methymna in ancient literature (Buchholz 1976: 151-62).

7.4 Population

The population of ancient Methymna has been estimated at 2,000-3,000 inhabitants (Zschietzschmann 1955a: 2110). Buchholz (1976: 47) dispenses with an estimate of the population size due to the lack of information regarding the size, structure, layout, and population density of residential areas of the city. Koldewey (1890: 16-7) estimated the area of the ancient city at 28.5 hectares, and the circumference of the walls at 2.9 km. He stated that the walls of the mediaeval fortress follow the outline of the ancient acropolis, which was obliterated in the construction process. Buchholz (1976: 40), in contrast, stated that nothing can be said about the origin, size, or shape of the ancient acropolis without further excavation, since no remains of the ancient fortification wall are visible underneath the mediaeval structure. The steep drop of the city-hill in the east and south implies that the ancient wall may have followed the edge of the hill like the mediaeval wall. In the north and west, however, where the slope is less precipitous, the ancient wall may have been significantly different from the mediaeval walls. Buchholz (1976: 46) suggested that the archaic walls had a length of 1.9 km if they included the harbor, and 1.7 km if they did not include the harbor. With the occupation and inclusion of the city-hill in the fifth century B.C., the city walls probably had a circumference of 2.6 km, and after 167 B.C., when Methymna accepted the people who had been forcefully relocated by the Romans from Antissa, the area of the city increased to include Dabia-East, and the walls grew to a length of close to 3 km—values that agree with Koldewey’s assessment (Buchholz 1976: 46-7).

7.5 Communications

The ancient harbor, in existence since at least the sixth century B.C., was located where the modern harbor is located today, at the southwestern tip of Dabia. The prehistoric settlement, *Palaia Methymna*, probably provided some kind of anchorage to seagoing ships off the north coast that was unprotected and exposed to the full force of wind and waves. The position of the Archaic settlement at the western portion of Dabia had the advantage of a natural cove formed by the concave angle in the coastline south of Dabia. A mole, 175 m long, protecting the harbor from the west, was built, allowing access to the harbor from the southeast. The root of the modern mole is identical to that of the ancient one, but the modern harbor basin is narrower than the ancient one. Precise dating of the ancient harbor is not possible. It is likely, however, that it is contemporary with the Archaic settlement of Dabia-West (Buchholz 1976: 47-9).

7.6 Economy

North Lesbos was very rich in timber, particularly oak and conifers. Furthermore, olives, figs, and especially wine (*cf.* Vergil, *Georg.* 2.89) were important products of the region around Methymna. As today, shellfish and fish were staples also in antiquity (Buchholz 1976: 34-5).

7.7 Water Supply

The supply of fresh water must have posed a difficult problem to the inhabitants of Methymna. Aquifers in the region lie very deep below ground. The digging of wells was, therefore, not a viable method to obtain water. Instead, a number of cisterns in Dabia indicate that rain water was collected and stored to secure a sufficient amount of water (Buchholz 1976: 58). The source of the aqueduct that supplied ancient Methymna is a spring at the northern slope of Hagios Elias, located 7 km east of the city. The aqueduct consisted of a terracotta pipeline of pipes with very thick walls—”ausserordentlich dickwandig” (Buchholz 1976: 57) (0.08 m internal diameter; length of individual pipe segments *ca.* 0.35 m), placed below ground and covered with earth and flat stones. The pipe had single lateral openings, spaced out *ca.* every 40 paces, “welche das fliessende Wasser mit der frischen Luft in Berührung bringt” (which brings the running water in contact with the fresh air) (Koldewey 1890: 18). The gradient of the pipeline down the slope of Hagios Elias was shallow. The aqueduct then traversed the depression between the Hagios Elias and the city of Methymna by means of an inverted siphon that ended in reservoir "C" (Appendix: Fig. 0.14), located, according to Koldewey's map at the foot of the acropolis, "um von hier aus in ziemlich bedeutendem Gefälle durch die Stadt vertheilt zu den verschiedenen Laufbrunnen geführt zu werden" (to be distributed from here with a rather significant gradient throughout the city to the different fountains). Reservoir "C" no longer exists (Buchholz 1976: 57). The inverted siphon near the acropolis consisted of terracotta pipes (0.04 m wall thickness) clad in thick masonry ("starkummauerte Thonrohre"). Near reservoir "C", the presumed end point of the inverted siphon, the pipeline consisted of perforated cubical blocks of trachyte (*ca.* 0.35 m width and height; *ca.* 0.31 m length; 0.085 m bore) with male-female joints. The external surfaces of the blocks were only roughly worked; the joint surfaces were smooth. Six of these blocks were found *in situ* near reservoir "C". Approximately in the middle of the depression, east of the acropolis, the aqueduct ran across a tower of roughly square cross-section (Fig. 7.6). In the late nineteenth century, the modern water supply line, too, ran across the same tower. At the top of the tower the water was decanted into an open basin, from which it flowed down again to continue west towards the city. Koldewey compared the tower with a similar structure at Mytilene, and with the *suterazi* in Istanbul. The purpose of the tower, according to Koldewey (1890: 18), was to refresh the water with oxygen on its long run through the pipeline. He dated the aqueduct to the fourth century B.C. Von Gerkan, however, suggested a date in the Roman Imperial period. Rutzen found perforated stones that were, no doubt, pipe segments of the inverted siphon built into the wall of a shepherds' hut and into field walls. The stone blocks consist of tuff, and the internal diameter of the perforation is 0.095 m. The external diameter of fragments of terracotta pipe found in the area east of the tower exactly fits into the joints of the stone pipe blocks. In contrast to Koldewey's reconstruction of the inverted siphon, Buchholz (1976: 57) suggested that the inverted siphon may have consisted mainly of ceramic pipes alternating with stone blocks. A similar system consisting of lead pipes and marble blocks was in use in Ephesos (Bammer 1972: 724). Rutzen was able to trace the line for a distance of *ca.* 1.5 km east-southeast towards the mountains. No more stone blocks occurred further away, perhaps they were not used beyond a certain distance from the tower (Buchholz 1976: 58). No more information about the layout of the aqueduct is available. The tower is the only known fixed point along the route of the aqueduct. The elevation of the source is not recorded in the relevant publications. The exact route of the aqueduct is known only in very rough outline. The end point of the aqueduct is no longer visible, and due to the inaccuracies in Koldewey's map, its exact position cannot be reconstructed without doubt. A comparison of Koldewey's map with a satellite image shows that the eastern portion of the map is very compressed in E-W direction, while the western coastline and the position of the castle are perfectly congruent (Appendix: Figs. 0.15 and 0.16).

During a site visit in the summer of 2006 most of the information given by Koldewey and Buchholz was confirmed to be accurate. The architectural and topographical evidence relevant to the aqueduct must be updated. It was not possible to take precise measurements during the site visit. Due to the location of the site at the international border with Turkey it is very difficult to procure a detailed topographical map at a scale of 1:25,000 or smaller. The remains of the tower in particular need to be measured and published, as neither Koldewey nor Buchholz provide any details about location, size, material, *etc*. The tower is located on a steep hillock that rises *ca.* 20 m above the surrounding plain (Fig. 7.2). The tower itself is approximately 5 m high and has a roughly square cross-section (*ca.* 2 x 2 m, tapering towards the top). The exact elevation of tower and hillock are unknown. A hand-held GPS gave the elevation of the hillock as 64 m a.s.l., with a possible margin of error of 10 m either way. The same GPS measured the elevation of the acropolis, 93 m according to Buchholz, as 104 m. On Koldewey's map the orientation of the tower is erroneous and must be rotated clockwise by *ca.* 20°. The bearing of the main axis of the tower is 107°. The west-northwest and the east-southeast faces of the tower have a deep vertical groove (width *ca.* ¼ of the total width of the tower) that run up to *ca.* 2/3 of the height of the tower (Fig. 7.4). At this height the tower is perforated by a quadrangular hole (same width as the grooves; slightly higher than wide). It is impossible to say without further investigation whether this hole contained the open basin that Koldewey saw. There does not seem to be any concavity in the top surface of the tower. At the foot of the northwestern face was a perforated stone block forming a 90°-elbow (Fig. 7.6). One opening had a male joint, the other a female one. The internal diameter is *ca.* 10 cm. Some fragments of terracotta pipe (wall thickness *ca.* 4 cm) were found that match the description by Koldewey and Buchholz. The terracotta pipe fragments fit precisely into the female joint of the stone elbow. A number of circular perforations, some with thin-walled terracotta pipes *in situ*, were found in each of the tower faces: 3 in the west-northwestern face, 2 in the north-northeastern face, 5 in the east-southeastern face, and 3 in the south-southwestern face.

These holes may be of recent date and may be related to the modern water supply system that Koldewey saw in operation. The perforations are located at head height and at double head height, between *ca.*0.3 m and 0.5 m from the edges of the tower. Those that pierce the vertical grooves from the side at a 90°-angle go all the way through the tower. Others do not penetrate through the entire width of the tower, but they may also have been clogged after they fell into disuse. The terracotta pipes that are still *in situ* are significantly thinner (*ca.* 1 cm wall thickness) than those that presumably formed part of the inverted siphon (Fig. 7.5).

During a site visit in the summer of 2006, it was possible to find and photograph without much difficulty *ca.* twenty perforated stone blocks from the ancient pipeline, with male or female joints showing, built into field walls, or lying on the surface in orchards or meadows (Figs. 7.7 and 7.8). Recording and processing of the scatter of these stones by means of a GIS-program would produce a likely trajectory of the inverted siphon. The furthest block was found *ca.* 1 km east-southeast of the tower.

Furthermore, a cistern (45 m a.s.l., measured with a hand-held GPS) of uncertain date was found during the site visit in 2006 at the foot of two hills west of the tower, and at a bearing that faces exactly the west-northwestern face of the tower (Figs. 7.9 and 7.10). The cistern is roughly circular, lined with field stones, and was covered with a modern steel-lid.

7.8 Discussion

Scattered pipe stone blocks are abundant, especially in areas west and east of the tower; less so in the north and south. The distribution of the blocks suggests that those that were not reused in buildings, *etc.*, were not moved far from the likely trajectory of the aqueduct. Terracotta pipe fragments that fit exactly the diameter of the stone blocks suggest that the pipe may have been a mixed ceramic-stone line. *Comparanda* exist, *e.g.* at Smyrna and Ephesus. Why the aqueduct was built across the isolated hillock that could have been easily circumvented is uncertain. The complicated arrangement of pipes, groves, and holes in the tower remains on the hillock indicate some distribution hub that required, probably for reasons of water pressure, the elevated position that the hillock offered. The two vertical grooves on two opposite faces of the tower, as well as a quadrangular opening near the top may be related to the primary use of the tower, where a pipeline ran up on one side, decanted into a basin, perhaps anchored in the opening, and ran down the other side. Smaller perforations and thin-walled terracotta pipes may have been inserted into the tower at a later date, perhaps as late as the nineteenth century, when Koldewey saw the tower in operation and incorporated into the contemporary water supply system of Methymna/Molyvos. The big number of secondary perforations may indicate that the tower was used as a node of distribution, from which numerous lines branched off to surrounding fields or farms.

The site of Methymna and the evidence related to the ancient aqueduct require a new, thorough survey. A recent, preferably digitized topographical map is necessary, in which the exact location of the water tower, the scatter of stone blocks, and the location of the cistern recorded in 2006 must be marked. The tower itself needs to be measured and properly documented. The location of a possible source and of a possible end point of the aqueduct must be determined. Local archives may provide information about the modern use of the aqueduct system, which seems to have been operational in the late nineteenth century.

Figure 7.1: View of the Site of *Palaia Methymna* from W

Figure 7.2: View of Castle and Tower from SE

Figure 7.3: View of Tower from ESE

Figure 7.4: View of Vertical Groove on WNW-Side of Tower

Figure 7.5: View of Terracotta Pipe *in situ* in WNW-Side of Tower

Figure 7.6: Stone Pipe Elbow at the Base of Tower

Figure 7.7: Random Stone Pipe Segment

Figure 7.8: Stone Pipe Fragments Built into a Field Wall

Figure 7.9: Interior of the Cistern

Figure 7.10: View of Tower from the Cistern

8. Alatri

8.1 Location

The site of ancient Aletrium, modern Alatri, is located at 41°43’N latitude and 13°20’E longitude, 75 km east-southeast of Rome in the Italian province of Lazio. Before and during the early Roman Republic, the region belonged to the territory of the Hernici, whose chief town was Anagnia, 15 km west of Aletrium. The ancient citadel was situated on a steep hill of limestone rock, today called Monte San Pietro, rising above the valley of the Cosa river to an elevation of 503 m a.s.l. In the north and west, where the principal city gates were located in antiquity, Monte San Pietro slopes down less precipitously than on the other sides, forming saddles that join with adjacent hills, namely Monte San Francesco to the west, and Monte Cappucini to the north. In the east, Monte San Pietro descends rapidly to the valley of the Cosa river, and in the south, to the valley of the Sacco river (De Minicis 1980: 1).

8.2 Climate

Climate data for Alatri are difficult to obtain. Due to the low population density in the central region of the Apennine Mountains, most weather stations in Italy are located along either the Tyrrhenian Sea or the Adriatic Sea. Potenza (240 km south, at 823 m a.s.l.) and Florence (285 km north, at 40 m a.s.l.) are the nearest inland locations for which both temperature and precipitation data are easily available. Rome lies 75 km west-northwest of Alatri, and must be included, although its relative proximity to the

Tyrrhenian Sea (25 km) and location on the coastal plain of the Tiber River has certainly a mitigating effect on the climate, when compared with the situation of Alatri. Thus the temperatures in Rome in winter are higher than in either Potenza or Florence (*e.g.* 6.8°C *vs.* 3.4°C and 5.3°C in January, the coldest month at all three stations). The yearly average temperature at Potenza (11.8°C) is significantly lower than at Florence (14.6°C) and Rome (15.0°C)—no doubt due to the high elevation of the recording station in Potenza.

The precipitation data show a progressively drier climate from north to south (Florence: 842.1 mm; Rome: 792.9 mm; Potenza: 588.7 mm). It is necessary to keep in mind that the precipitation data for Florence and Rome were collected during a significantly longer time than those for Potenza (Florence: 1821-1977; Rome: 1782-1970; Potenza: 1961-1990). The data from Potenza may, therefore, reflect recent climate change, and in the past the difference between Potenza and the other two stations may not have been as pronounced. A similar caveat applies to the relatively high average temperature at Rome (15.0°C, from data collected between 1961 and 1970).

Average temperature data for Potenza (40°37’N 15°48’E; 823 m a.s.l.) derived from GHCN 1, from 229 months between 1961 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	3.4	3.9	5.9	9.6	13.8	17.2	20.5	20.4	17.4	13.0	8.5	4.8	11.8

Average precipitation data for Potenza (40°37’N 15°48’E; 823 m a.s.l.) derived from GHCN 1, from 219 months between 1961 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	55.5	48.7	52.1	48.5	35.6	33.5	28.1	38.2	45.0	56.3	70.7	75.1	588.7

Average temperature data for Florence-Peretola (43°48’N 11°12’E; 40 m a.s.l.) derived from GHCN 1, from 990 months between 1832 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	5.3	6.7	9.5	13.3	17.9	22.0	24.7	24.1	20.3	15.3	10.0	6.5	14.6

Average precipitation data for Florence-Peretola (43°48’N 11°12’E; 40 m a.s.l.) derived from GHCN 1, from 884 months between 1821 and 1977 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	64.1	61.5	69.4	70.5	73.3	56.4	34.2	46.9	83.4	99.1	103.4	79.4	842.1

Average temperature data for Rome-Ciampino (41°48’N 12°36’E; 129 m a.s.l.) derived from GHCN 1, from 120 months between 1961 and 1970 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	6.8	7.9	9.9	13.3	17.0	21.0	23.8	23.6	20.6	16.1	12.4	8.0	15.0

Average precipitation data for Rome-Ciampino (41°48’N 12°36’E; 131 m a.s.l.; a different station than the one supplying the temperature data) derived from GHCN 1, from 1188 months between 1782 and 1970 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	81.2	63.2	70.3	55.7	53.0	36.4	17.5	27.5	60.9	117.7	111.0	97.9	792.9

Given this information, it is difficult to deduce an accurate climatic scenario for Alatri. Potenza is similar to Alatri in terms of elevation (823 m and 503 m) and general inland location. The data for Potenza, therefore, though they represent only 30 years of data gathering, probably reflect the situation at Alatri more closely than the data for either Florence or Rome. With the above limitations in mind, the climate at Alatri is at the borderline between temperate and typically Mediterranean with temperate, dry summers, and cool, damp winters. It follows that in Potenza and, by extension, in Alatri, on the long-term average, the months from June to August must be considered arid, though June and August are almost exactly at the borderline (June: 17.2°C and 33.5 mm; August: 20.4°C and 38.2 mm).

8.3 History

Aletrium was probably founded in the sixth century B.C. During the Second Samnite War (326-304 B.C.), the *Hernici* revolted against Rome. Unlike, for example, the neighboring city of Anagnia, Aletrium, along with Ferentinae and Verulae, remained a loyal ally of Rome. Aletrium was rewarded for loyalty to Rome by being made a *municipium* in 306 B.C. (Livy, 9.42-4). Cicero also identified Aletrium as a *municipium* (Cic. *Clu.* 46). The city remained a *municipium* throughout the imperial period (CIL X 5808). Since Aletrium is only rarely mentioned in ancient literature (Salmon 1976: 36), no information about population size or economical basis is available.

According to Salmon (1976: 36), the principal monument of the city is the double circuit of “massive walls, the finest and most remarkable example of polygonal construction in Italy." The walls consist of irregularly cut limestone blocks, up to 2 x 3 m in size, and fitted together without mortar. The elliptical outer circuit wall is 4 km long, and the trapezoidal inner circuit wall is more than 600 m long. Both well preserved circuits are thought to date to some time between the fourth and the first centuries B.C. (Salmon 1976: 36). Routes of communication with Aletrium were rather insignificant. Aletrium was located some 10 km northeast of the Via Latina, one of the oldest roads between Rome and Campania. A minor road, whose location is only approximate, branched off from the Via Latina and ran north through Aletrium to the Villa Neronis (Talbert 2000: 44).

8.4 Water Supply

According to Secchi (1864: 406), Aletrium was "altogether deprived of water," due to its position on a hilltop. It was, therefore, necessary to convey water to the citadel from a remote source by means of an inverted siphon. A Republican Roman inscription from Alatri (*CIL* X 5807) reports that Lucius Betilienus Varus had a number of structures constructed in Aletrium, among which: "*lacum balinearium, lacum ad| portam, aquam in opidum adou(c(entem)),| arduom pedes CCCXↆ fornicesq(ue)| fecit, fistulas soledas fecit.*" (He built a basin for the baths; at the gate a basin that leads water into the town, to a height difference of 340 feet, and arches; he made firm lead pipes.) A second, very fragmentary, inscription also mentions "*aquam in oppi[dum---]| Pegasus Augus[ti l(ibertus)*----" (… water into the town… Pegasus, (freedman) of Augustus…). The context of the second, fragmentary inscription is entirely lost (Gasperini 1965: 16-9, 34). The first inscription dates the aqueduct to 134 B.C. or earlier (de Montauzan 1909: 194). Furthermore, the mention of *fistulas* in the inscription indicates that the pipes were made of lead. Randomly shaped globules of lead found along the route of the aqueduct indicate that the pipes consisted not of bent lead sheets, soldered at the seams, but that they were cast at the construction site. Intact lead-pipe segments (0.17 m external diameter), found at the slopes of Monte Paielli and Monte Cappucini, lack soldered longitudinal seams. Their wall thickness increased with increasing water pressure, from 10 mm "half way up Monte Paielli" (auf halber Bergeshöhe), *i.e.* perhaps 440 m a.s.l., to 12 mm at an elevation of 50 m above the streambed (*i.e.* 422 m a.s.l.), and 32 to 35 mm at the lowest point of the inverted siphon (Bassel 1882: 436). A piece of a terracotta mould, attached to a piece of lead pipe, showed that the pipes must have been cast standing up. Their exterior diameter was constant (0.17 m), but their wall thickness was not uniform; it changed to accommodate the requirements of water pressure at different heights along the inverted siphon. Since the shop where the pipes were cast was mobile and moved along with the construction site along the inverted siphon, it is not surprising that lead globules were found in various places along the route of the pipeline (Bassel 1919: 8).

The various lead pipe fragments show definite traces of hammering. During the manufacturing process, the cast pipes were beaten with a hammer over a wooden core in an attempt to increase their strength (Bassel 1882: 436). It is wrong, however, to say that the hammering increased the density of the pipe walls (*e.g.*, de Montauzan 1909: 196), since solids are incompressible. The cold working of a metal causes a change in the crystal structure, which increases the hardness, but not the density, of the material. Since *fistula* is the standard Latin term for a lead pipe, the modifying adjective *soleda* may be an indication of the manufacturing process by casting and hammering, and, therefore, refer to the absence of a soldered seam that weakens a pipe (Hodge 1983: 193, n. 54). Biernacka-Lubanska (1998) does not mention this technique in her study on Roman lead pipe production technology.

Secchi (1864: 407) claims that pipes of bronze were discovered near the acropolis. As a result, he links the term "*fistula soleda*" from the inscription to these bronze pipes. The pipe material was the cause of much discussion in the nineteenth century, to a point where the existence of the inverted siphon was doubted altogether. Secchi (1864: 406) stated that the town was "traversed with pipes of lead and terracotta." He found a piece of terracotta pipe with an internal diameter of 0.345 m and a wall thickness of 0.061 m and thought it was a piece from the inverted siphon. In 1879, di Tucci vehemently attacked this opinion. He stated that under a pressure of more than 100 m of water column, water would have percolated through the pores of a terracotta pipe, and that terracotta would not have been able to resist mechanically such high pressures in the first place. Whether this sweeping statement is true depends obviously on the type of clay, the wall thickness, and the manufacturing process of the terracotta pipes. The analysis of the technical parameters that determine the truthfulness of the statement is a task for experimental archaeology. Di Tucci went so far to state that even a lead pipe, such as it is prescribed by Vitruvius (*De arch.* 8.6.4), would have been unable to survive such high pressure. His conclusion was, therefore, that the citadel of Alatri must have been supplied with water not by means of an inverted siphon, but by means of an arcaded bridge in a location where such a bridge would have been as short as possible (de Montauzan 1909: 194-95).

Bassel, too, reported the discovery of a terracotta pipe (0.54 m long, internal diameter 0.17 m, wall thickness 0.055 m) on the east slope of Monte San Pietro, in a masonry channel, surrounded by packed earth. Bassel, like di Tucci, concluded that a pipe of such material and dimensions would not have been able to withstand the pressure in the inverted siphon, and suggested that the terracotta pipe may have been part of an extensive drainage system that was observed by both di Tucci and Secchi (Bassel 1881a: 135). In 1919 Bassel changed his conclusion and suggested that the "pipe" he had described in 1881 was a terracotta mould used in the casting of the lead pipes (Bassel 1919: 8).

"Barbarians, and afterwards […] peasants" demolished the channel feeding the header tank of the inverted siphon, so that Secchi was able to find only its foundations (Secchi 1864: 407). Bassel found "traces of a small aqueduct" (Spuren eines kleinen Aquäductes) on Monte Paielli. The aqueduct consisted of a channel cut into the underground, faced with masonry, lined with *opus caementicium*, and covered with a layer of sinter. This channel was most likely covered in antiquity. Where exactly the water source that fed it was located is not known. The channel ran south from Vico nel

Lazio, skirting the east slope of Monte Paielli, and was protected against erosion by a retaining wall on its downslope side. Bassel found, furthermore, a circular basin at an elevation of 481 m a.s.l. on the southeast slope of Monte Paielli in a saddle between the hill proper and its southeastern projection. This basin was most likely the header tank of the inverted siphon that supplied water to ancient Aletrium (Bassel 1881b: 122).

The length of the inverted siphon from the basin at Monte Paielli to the citadel of Alatri is *ca.* 3.3 km (Fig. 8.1; Appendix: Figs. 0.17 and 0.18). Parts of the substructure of the inverted siphon were visible to Bassel some 300 m upstream from the confluence of the Cosa and the Purpuro streams, north of Alatri between Monte Secco and Monte Paielli. The aqueduct crossed the two streams on arched bridges, and ran over a solid wall where the terrain was higher. Each of the two crossings had a length of approximately 250 m; between the crossings a distance of some 70 m was entirely without a trace of substructure. Bassel gave the elevation at this point as 390 m a.s.l., and measured the bottom of the streambed of the Purpuro at 372 m a.s.l. (Appendix: Fig. 0.19). Bassel was convinced that the deepest point of the inverted siphon must have been between the crossings of the two streams. In order to keep the pipeline, which was under high pressure, as short as possible, it was desirable to make the inverted siphon rise again as early as possible. The most convenient route was across Monte Secco and Monte Cappucini up to Alatri. Bassel was very conscious of the problems that can occur at local high points in a pipeline. He therefore suggests a route along the western slopes of these two intermediate hills, not straight across, “bei welcher Scheitelstrecken und somit

Luftventile vermieden sind.” (… in which high points, and hence air valves, are avoided) (Bassel 1881b: 122).

Contrary to Bassel, Lewis (1999: p. 159, fig. 1) points out the analogy between the inverted siphon at Alatri and those at Pergamum and Smyrna (Appendix: Figs. 0.9 and 0.13). Lewis suggests that the pipeline did cross the intermediate hills, Monte Secco (455 m a.s.l.) and Monte Cappucini (*ca.* 465 m a.s.l.). Same as the Madradağ pipeline at Pergamum and the Karapınar pipeline at Smyrna, the inverted siphon at Alatri was built straight across the intermediate hills in order to avoid the need for anchoring against lateral displacement in the event of earthquakes or landslides. Monogram stamps on terracotta pipes from the Madradağ aqueduct at Pergamum establish, according to Lewis, a link with the family of the Betilieni, who were involved in pottery and brick manufacture, and in trade with the eastern Mediterranean region, as an inscription from Delos and stamps on amphorae and bricks prove (*CIL* IX 6079 11-14, XV 2294, 2296, 2312). There is a possibility that the Betilieni, who were commercially involved in Asia Minor, and who were involved in the construction of the aqueduct at Aletrium, may have supplied terracotta pipes for aqueducts at Pergamum, and may have brought from Pergamum the idea of the inverted siphon and the layout incorporating intermediate hills to Italy. Lewis (1999: 162) concedes that the possible link between the Betilieni and Pergamum is “worth observing, though not stressing because other solutions may be possible.”

The *lacus ad portam* was located at an elevation of 479 m a.s.l.—2 m lower than the circular basin on the slope of Monte Paielli—near the Porta San Pietro, the northern city gate of Alatri. The streambed of the Purpuro is at an elevation of 372 m a.s.l. The difference in elevation between the streambed of the Purpuro and the Porta San Pietro, which is located 6 m below the *lacus*, *i.e.* at 473 m a.s.l., gives a vertical distance of 101 m. This distance (341.2 Roman feet) corresponds very closely with the 340 Roman feet given in the inscription of Betilienus Varus (Bassel 1881b: 122). From the values for the elevation of the presumed header and receiving tanks (481 m and 479 m), it follows that the inverted siphon at Alatri operated with a head of approximately 2 m, depending on the water level in each of the two tanks. Since the aqueduct did not cross the Purpuro on the level of the streambed, but on arches 16.8 m above the streambed, Bassel (1881a: 134-35) initially suspected some inconsistency between the physical remains and the height given in the inscription. Later, however, based on the account of two local witnesses who found pieces of lead pipe in the city of Alatri, above the *lacus ad portam*, Bassel stated, without mentioning an elevation, that the inverted siphon must have brought up water *ad arcem* (Bassel 1919: 8). In contrast, Laurenti's reconstruction (1987: 304), reproduced in Lewis' diagram (1999: 159, fig. 1), shows that the header tank was at an elevation of *ca.* 490 m a.s.l., and the receiving tank at an elevation of 473 m a.s.l., *i.e.* at the elevation of the Porta San Pietro.

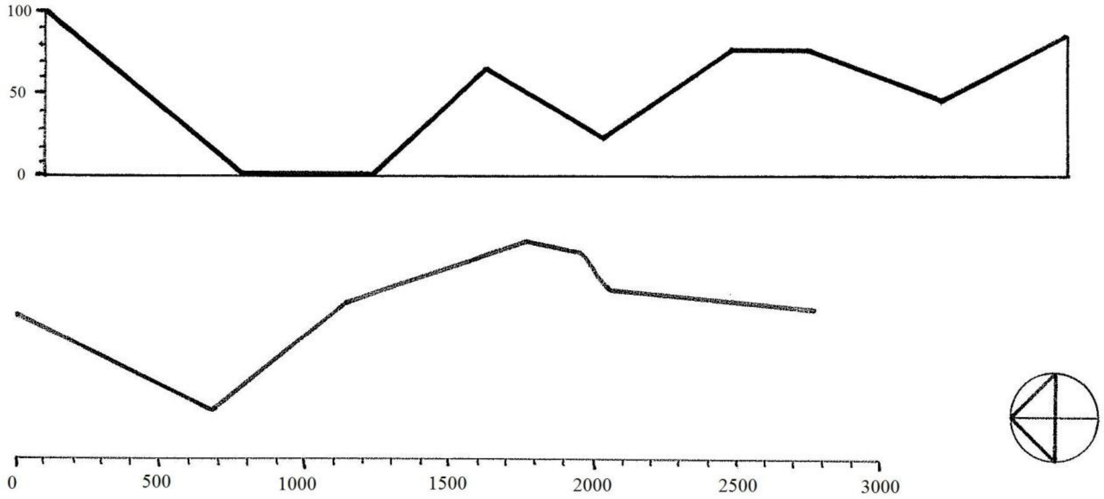

Figure 8.1: Evolved Elevation and Plan Pipeline Alatri (Flow Direction Left to Right)

9. Lugdunum

9.1 Location

The ancient site of Lugdunum, modern Lyon, is located at 45°46′1″N latitude and 4°50′3″E longitude in the French *Département* of Rhône, at the confluence of the rivers Rhône (ancient Rhodanus) and Saône (ancient Arar). The name Lugdunum is a derivative of the name of the Celtic god *Lug* and the Gallic word *dunon*, meaning castle or fortress. The original Gallic settlement was located at an elevation of 292 m a.s.l. on a hill, in modern Fourvière, on the right bank of the Arar. The name Fourvière derives from the Latin *forum vetus*, *i.e.* the old forum of the early Roman city, which was located on top of the hill. A second, nearby settlement of Gauls, who had been displaced by the Allobroges from the region of modern Vienne, grew on the narrow strip of land between the two rivers where the Arar flows into the Rhodanus at a very sharp angle (Cramer 1955: 1719). Today, Lyon is the third largest city in France with a population of *ca.* 460,000 inhabitants, and *ca.* 1.2 million inhabitants in the larger agglomeration known as Grand Lyon. Therefore much of the ancient city is concealed under buildings and structures that were created during more than two millennia of continuous occupation.

9.2 Climate

The weather station at Lyon is located at an elevation of 201 m a.s.l. The average temperature over the year is 11.0°C. The data for average temperatures, derived from GHCN 2 Beta (Hoare 2006) for a period of 1444 months between 1851 and 1991 are:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	2.0	3.6	6.8	10.4	14.2	17.9	20.4	19.7	16.5	11.5	6.2	2.5	11.0

The data for average precipitation, derived from GHCN 1 (Hoare 2006), show an annual average of 777.9 mm calculated over 1791 months between 1841 and 1990.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	43.2	41.0	51.7	61.0	75.1	78.1	64.9	79.0	76.8	86.8	68.3	50.9	777.9

The climate at Lyon is typical of the temperate climate region with warm, damp summers and cool, damp winters. At Lyon, in contrast to all other sites under investigation in this work, rainfall is sufficient year round. The construction of an aqueduct at a site located in a temperate climate zone could be, upon first glance, interpreted as not a response to a bare necessity of life but rather a matter of convenience. Sufficient year-round precipitation seems to suggest that no water need be brought to the site from a distance, especially at the junction of two rivers of significant size. With the rivers flowing far below the elevated town, though, and the site only poorly supplied with springs or opportunities to dig wells an aqueduct (or four, as in the case of Lugdunum), makes access to water much easier. Perhaps more importantly, the aqueduct also serves as a symbol of Roman status, power, and benevolence in a recently founded colony in Gallic territory that is growing in importance as a Roman administrative capital (*cf.* below).

9.3 History

The two native settlements at the confluence of the rivers Rhône and Saône came under Roman control during the time of Julius Caesar, and L. Munatius Plancus founded a Roman colony in 43 B.C. (Tac. *Hist.* 1.65.2). The city was located at the border of the province *Narbonensis*, and gave its name to the province *Lugdunensis*. In 27 B.C., Lugdunum became the administrative capital of *tres Galliae* (*Lugdunensis*, *Aquitania*, *Belgica*). The Roman colony grew south of Fourvière around a granite-paved *decumanus* and *cardo*. In the first and second centuries A.D., the city expanded on the east slope of Fourvière, along both banks of the Arar, and on the Island of the Canabae, the long peninsula formed by the two rivers of the city (Leglay 1976: 530).

The oldest Roman theatre in Gaul was built at Lugdunum on the slope of the Fourvière hill under Augustus in 16-14 B.C. In its original form it could accommodate 4,500 spectators. Under Hadrian, the theatre was extended to seat an audience of 10,700 (Leglay 1976: 528). Lugdunum was the only city in Gaul besides Vienne that had two theatres. The smaller *odeum* was located near the theatre and could seat 3,000 spectators. The city also had a stadium and an amphitheater (Leglay 1976: 529).

Lugdunum was the birthplace of the emperor Claudius (10 B.C.). During Claudius' reign (A.D. 41-54) the city received special favors, such as access to the Roman senate for Gallic chiefs (Tac. *Ann.* 11.23). A bronze plaque, the Claudius Tablet, kept in the Gallo-Roman Museum Lyon-Fourvière, preserves part of a speech given to the Roman Senate in A.D. 48, in which Claudius supports the request of the Gallic leaders for access to Roman magistracies (Leglay 1976: 529).

In A.D. 65, Lugdunum was destroyed by a fire (Tac. *Ann.* 15.13). The city flourished again, especially under Hadrian. In A.D. 197 Lugdunum was partially destroyed in the struggle between Septimius Severus and Clodius Albinus (Leglay 1976: 528). The importance of Lugdunum declined further when Trier became one of the four capitals of the Tetrarchy (Cramer 1955: 1722). Lugdunum was imperial residence of Domitian and Hadrian, and it was the birthplace of Caracalla (A.D. 186.).

9.4 Economy and Communications

Lugdunum was the seat of an important Roman mint, the only one outside of Rome that was authorized to mint Imperial coins during the early Empire (Cramer 1955: 1719). The position of Lugdunum at the confluence of two rivers made it an important node of communications and trade. The Rhodanus was the main artery for traffic between Gaul and the Mediterranean Sea, particularly Massilia, and was the first stage of river and land routes between the Mediterranean and the North Sea. The first port of the city was located on the west bank of the Rhodanus, south of the confluence with the Arar. During the reign of Hadrian (A.D. 117-138) the port and docks were moved 1 km upstream, closer to the commercial center of Canabae (Leglay 1976: 530). Water transport was supplemented with excellent long-distance overland traffic on well-maintained roads that go back to the time of Agrippa. Lugdunum traded in wine, olive oil, fruit, salted pork, Baltic amber, British tin, and Gallic garments (Cramer 1955: 1721). It is telling for the affluence of the early Roman city that after the fire in Rome of A.D. 64, Lugdunum sent 4 million sesterces to the city. When Lugdunum suffered the same fate one year later, Rome responded in kind (Cramer 1955: 1720). Within a short time of its foundation, the city had tens of thousands of inhabitants (Burdy 1991a: 7), necessitating a carefully designed water-supply system.

9.5 Water Supply system

Burdy (2002a: 19) qualifies the water resources at the higher elevations of Lugdunum as mediocre. A number of springs issued from two aquifers at Fourvière. One aquifer issued in several springs at the lower level of the hill (165 m a.s.l.), the other at an elevation of 220-240 m a.s.l. The inhabitants tapped these aquifers not only by using the springs, but also by means of wells (Burdy 2002a: 19). In addition, a large number of cisterns collected and stored rain water. More than 50 such cisterns were found in private dwellings in the areas that have been excavated to date. Many more must have been in use in antiquity throughout the city. These cisterns were relatively small (2-3 m side length; 3-5 m deep; 10-30 cubic meters capacity) and generally rectangular (Burdy 2002a: 20).

While springs, wells, and cisterns were sufficient to fulfill the basic water needs, the increasing population during the Roman period, and, above all, the importance of Lugdunum as capital of the Three Gauls, made it necessary to build a water supply system that was a reflection of the grandeur of Rome and of the power of the Empire (Burdy 1991a: 7). Following the model of the city of Rome, the city of Lugdunum, too, wanted clean running water. Consequently, four aqueducts were built to supply the city. The sources lay on three mountains on the western side of the Arar: Mont d’Or, Monts du Lyonnais, and Mont Pilat. The aqueducts were built to supply primarily the higher elevations of the city on the right bank of the Arar, because access to river water was difficult from Fourvière (Burdy 2002a: 19).

The Mont d’Or (625 m a.s.l.), the source of the Mont d’Or aqueduct, is located 10 km north of Lugdunum. The water from its springs is low in calcium carbonate and of good quality. The Monts du Lyonnais are located 15 km west of Lugdunum. They form a 20-km-long mountain chain that descends in elevation from 930 m in the south to 550 m in the north. These mountains cause damp westerly winds from the Atlantic to rise and the moisture in the air to precipitate as rain. Springs are, therefore, abundant in the Monts du Lyonnais, and their water is of excellent quality. The Brévenne aqueduct and the

Yzeron aqueduct originate here. The Mont Pilat, part of the Cévennes Mountains (maximum elevation 1,434 m a.s.l.), is located 40 km south of Lugdunum. Moist air from the Atlantic and from the Mediterranean Sea cause abundant precipitation and benefit the formation of large rivers, one of which is the Gier. The Mont Pilat is the origin of the Gier aqueduct.

Between these mountains and the site of Lugdunum/Lyon extends the Plateau Lyonnais at a width of *ca.* 10 km and at an elevation of 300-400 m a.s.l. This plateau is cut by a valley *ca.* 2 km wide that is 90-140 m deeper than the plateau itself. The valley is crescent shaped and runs from the western bank of the Saône in the north to the western bank of the Rhône in the south. The straight distance between the tips of the crescent is *ca.* 10 km. The aqueducts supplying Lugdunum could not circumvent this valley. Therefore, it was necessary to convey the water across this valley by means of inverted siphons (Burdy 2002a: 21-2). Since the water supply systems brought water up to or near the height of Fourvière (296 m a.s.l.), a second, more immediate obstacle was the Col de Trion (265 m a.s.l.), a depression separating Fourvière from the surrounding plateau (Burdy 2002a: 135). Two of the four aqueducts that supplied Lugdunum with water, the Mont d’Or and the Yzeron, are from the period of Augustus. The Brévenne aqueduct was built under Claudius, and the Gier aqueduct was built under Hadrian (Leglay 1976: 530). The four aqueducts contained nine inverted siphons. This number represents *ca.* one third of the total known such structures that date to the Roman period.

Modern research on the aqueducts at Lyon began in the early twentieth century with Germain de Montauzan (1909), a French civil engineer. His work is still today an important resource for the scholarship on Roman inverted siphons. Recent studies of the water-supply system of Lugdunum have been conducted, above all, by Jean Burdy (1987, 1991a, 1991b, 1993, 1996, 2002a), who synthesized and updated de Montauzan's work.

The Mont d'Or aqueduct is known from remains found in *ca.* fifty places along its 26 km-long route (Appendix: Fig. 0.21). The aqueduct started at an elevation of 372 m a.s.l., where it captured the water from the springs of a stream called Thou. No ancient structures remain at the head of the aqueduct. The first known point lies 850 m downstream, at an elevation of 310 m a.s.l. Two inverted siphons crossed intermediate valleys along its course, one 420 m long and 30 m deep (head loss 8 m), the other 3,500 m long and 70 m deep (head loss 11 m). No remains of these inverted siphons are extant, and their existence can only be inferred from the topography. It is easily possible, though, to determine the locations of header and receiving tank of the second inverted siphon of this aqueduct (Burdy 2002a: 137). Remains of a distribution channel in Lugdunum are visible at an elevation of 261 m a.s.l. just west of Fourvière (Burdy 2002a: 75). The flow rate delivered by the Mont d'Or aqueduct was *ca.* 4,000 cubic meters per day (Burdy 2002a: 174).

One of the four aqueducts is known as the Yzeron aqueduct, named after the modern town from where the longest branch of the ancient aqueduct presumably took its start. The date of its construction was probably between 20 and 10 B.C. Although the remains of this aqueduct are badly preserved, some information has been extracted from the material available. The longest branch of the system had a length of *ca.* 40 km with a drop in level of 442 m from source to town, giving it an average gradient of 1.1%. The main aqueduct receives at least two affluent branches. It is not completely sure that there was indeed a connection of the third and longest branch, the Yzeron branch, to the main line (Burdy 1991a: 4).

The route of the Yzeron aqueduct is still unknown in places (Appendix: Fig. 0.25). It collected the water from three different sources. The longest branch has been traced from remains in *ca.* thirty places. It captured the water of the Yzeron stream, from which the aqueduct takes its name. The starting point of the aqueduct has not been found, but it was likely located at an elevation of *ca.* 720-750 m a.s.l., several hundred meters upstream from the first visible traces of the channel. Throughout the entire length of this branch a terracotta pipe has been laid in the aqueduct channel, presumably in the late Gallo-Roman period ("d'époque gallo-romaine tardive"), to deal with the deterioration of the channel. The starting point of a second branch that supplied this aqueduct is likewise unknown. Its route runs through the centre of the modern town of Vaugneray. The channel of this branch included drop shafts. It joined a third branch, that of Grézieu, between Montolvet and l'Araby. This third branch is considered the main channel of the aqueduct. The route is known downstream of the town of Montferrat. Due to its very steep gradient, the aqueduct contained many drop shafts. A total of more than twelve drop shafts made this branch a hydraulic stairway ("escalier hydraulique"). Near the village of Grézieu this channel was probably joined by a fourth branch, Mercier, of which only *ca.* 100 m are visible. The channel arrived at Tupinier at an altitude of 313 m. At this point was located the header tank of the double inverted siphon (Burdy 2002a: 72).

The double inverted siphon ran in an almost straight line for a total length of 5.8 km. The first portion was 2.2 km long and descended from an altitude of 313 m a.s.l. at the header tank to 280 m at the lowest point of the first segment. It then rose again to

306 m, presumably decanting into an open basin at the top of a tower. The remains of the tower consist of two pillars, *ca.* 12 m tall, known today as Tourillons de Craponne, and three more pillar bases (Fig. 9.2; Appendix: Figs. 0.27 and 0.28). The height of the intact tower must have been *ca.* 16 m. The modern reconstruction of the tower, with its six arches supporting the two ramps and the open basin on top of the central pillar, is based on the model of the towers at Aspendos. The width of the inverted siphon was *ca.* 4.4 m (Burdy 2002a: 138-9).

The drop of the first half of the inverted siphon is 33 m, and the head loss is 7 m. The second segment, between the Tourillons de Craponne and the receiving tank, was 3.6 km long. The low point of the second segment was presumably an arcaded bridge across the Charbonnières brook at 215 m a.s.l., from where it reached the receiving tank at 273 m a.s.l. The second segment had a drop of 98 m and a head loss of 40 m (Burdy 1991a: 100-1). The volume flow rate of the Yzeron aqueduct was *ca.* 6,000 cubic meters per day (Burdy 2002a: 174). The tower at Craponne was built as a vent to remove an air bubble that formed downstream of the intermediate high point when the inverted siphon was filled. The topography west of Lugdunum as well as cost calculations (*cf.* Chapter 16) apparently did not allow a circumvention of the intermediate high point.

The Brévenne aqueduct had a total length of 70 km, which makes it the tenth longest ancient aqueduct (Appendix: Fig. 0.20). It included two arcaded bridges, both of which have completely disappeared, and one inverted siphon, ruins of which still exist. Despite more than 160 spots where remains of the channel were found, the Brévenne aqueduct is poorly known. Its starting point was located on the western slope of the Monts du Lyonnais, facing away from Lugdunum. The location of its starting point required the aqueduct to run in a wide curve starting in northeasterly direction, turning east, then south in the direction of Lugdunum. The water was supplied by numerous springs in the region, at an elevation of 630 m a.s.l. Several small ancient feeder channels were found during modern construction works. The inverted siphon traversed the Plateau Lyonnais. It had a length of 3,500 m, a depth of 90 m, and a head loss of 40 m. The ramp that used to support the pipeline on its ascent to the receiving tank is remarkably well preserved. It is possible, though not certain, that the Brèvenne aqueduct contained a second inverted siphon that crossed the Col de Trion. This hypothetical inverted siphon would have been 500 m long and *ca.* 20 m deep (Burdy 2002a: 65-9, 136). The volume flow rate of the Brévenne aqueduct was *ca.* 10,000 cubic meters per day (Burdy 2002a: 174).

The Gier aqueduct has a total length of 86 km (Appendix: Figs. 0.22, 0.23, and 0.24). The aqueduct contained some 40 bridges, five solid and eight arcaded substructures, 11 tunnels, and four inverted siphons. The Gier aqueduct began at an elevation of 405 m a.s.l., and arrived at the highest point in the city, at an elevation of 300 m. The aqueduct was fed directly by the river Gier at the foot of Mont Pilat. This was its only source (Burdy 2002a: 39-40). In its course the aqueduct negotiated the valley of la Duréze. It did so by an inverted siphon that cut through the valley, and by means of a free-surface channel that ran around the valley, forming a loop of 11.5 km. The inverted siphon and the channel branched off from each other on one side of the valley and joined each other again at the other side. The inverted siphon had a length of 700 m and a depth of 79 m. The head loss between header and receiving tank was 5.8 m. The inverted siphon consisted of ten lead pipes side by side. (Burdy 2002a: 41-2, 136, 143).

Closer to Lugdunum the aqueduct had to cross the valley of the river Garon. Traversing the valley by means of a free-surface channel would have meant a detour of 15 km that would have required the construction of at least two large aqueduct bridges. The loss in elevation over that long a stretch of channel would have been *ca.* 15 m (Burdy 2002a: 50-2). Instead, the designers built an inverted siphon (1210 m length; 93.5 m depth; 8.8 m head loss) that crossed the Garon (Burdy 2002a: 53, 136). The header tank is relatively well preserved. It is well known by the name of the nearby village of Soucieu. The header tank consisted of a rectangular basin (6.2 m transversally; 3.1 m longitudinally; barrel vaulted) with a square (1.55 x 1.55 m) opening for inspection and access at the top. The water discharged into the inverted siphon through 10 lead pipes, arranged side by side. Four of the discharge openings (oval; 0.26 m wide; 0.31 m high) for the pipes are still extant. The pipes descended to the horizontal portion on a 5-m-wide ramp (Burdy 2002a: 53). The horizontal stretch included a bridge (210 m long; 7.35 m wide; 21 m high at its highest point; originally 23 arches) across the Garon. The pillars of the arches were as wide as the bridge itself (7.35 m) and 3.05 m thick. Originally some of the pillars had arches also in the transversal direction, but these were all filled in with masonry, except in the last pillar downstream. Burdy (2002a: 54) calls these transversal arches “une erreur architecturale” (an architectural mistake). The bridge carried the 10 pipes side by side and was probably also used by construction and maintenance crews for access to the pipes. The receiving tank must have been very similar to the header tank. Only the substructure (6.2 m x 3.4 m) of the receiving tank survives. It is preceded by a 5-m-wide ascending ramp. The receiving tank discharged into an open channel that was carried on an arched bridge. Since the channel has disappeared in this place, it is unknown how wide it was. The width of the surviving substructure is 1.85 m (Burdy 2002a: 56).

The third inverted siphon of the Gier aqueduct crossed the Yzeron valley and is located *ca.* 4 km downstream from the second. It had a length of 2,660 m, a depth of 122.3 m, a head loss of 7.9 m, and consisted of eleven pipes side by side. The header tank, very poorly preserved, was located on a large pillar 10.5 m above ground. It was rectangular (7.15 m x 3.1 m on the outside) and covered with a barrel vault. The channel that entered it was 2.15 m wide on the outside, and the ramp descending from it, which carried the pipes, was 5.85 m wide (Burdy 2002a: 57, 59-60, 143).

The fourth and final inverted siphon of the Gier aqueduct was 575 m long, 38 m deep, and had a head loss of 2.3 m. It was built to traverse a depression called Col de Trion, just southwest of Fourvière. The barrel-vaulted, rectangular header tank (5.5 m wide; 3.2 m long) was built on an enormous pillar, 11 m high. It was filled by a channel with an outside width of 2.18 m. Four of originally nine orifices that held the lead pipes on the downstream side are still extant. The ramp leading down from the header tank was 5 m wide. The remains of the receiving tank were torn down in 1846, but its location in Lyon is known (Burdy 2002a: 62-3). The volume flow rate of the Gier aqueduct was *ca.* 12,000 cubic meters per day (Burdy 2002a: 174).

The pipes of the inverted siphons must have consisted of lead, as the high pressures at the bottom of the pipelines could be handled only by either stone or metal. Neither lead nor stone pipe fragments were found, but a spectroscopic analysis of mortar from the orifices of the header tank at Soucieu showed results that proved that lead was indeed the pipe material. Following from the size of the surviving orifices in the tanks of two inverted siphons of the Gier aqueduct, the outer pipe diameter was 0.23 m. Depending on the depth of the inverted siphons, and, therefore, the maximum static pressure in the pipes, the necessary pipe wall thickness was between 1.15 cm and 3.4 cm for the inverted siphons of the Gier aqueduct. It is possible that the wall thickness was varied along the height of the same inverted siphon, such as was done at Alatri (Bassel 1919: 8), to avoid the waste of metal. But no evidence for or against such practice exists at Lyon (Burdy 2002a: 153-4). The pipes have left impressions in the mortar of the orifices of the extant tanks of the Gier aqueduct. The impressions show traces of a longitudinal seam in the pipe, suggesting that they were manufactured of rolled and soldered sheets of lead, perhaps 10 Roman feet long (Burdy 2002a: 153). It is possible, however, that the pipes that had to withstand higher pressures further down the inverted siphon were cast rather than rolled and soldered, as a longitudinal seam would have represented a very weak line running along the length of the pipe. As noted above, cast pipes were used at Alatri (Bassel 1919: 8) and Pergamum (Fahlbusch 1982: 74). Burdy (2002a: 157) calculated the weight of the lead required for all four inverted siphons of the Gier aqueduct at a total of 10,000 tons.

The structural elements of the aqueducts were all built of locally available stone. The immediately available material was limestone for the Mont d’Or aqueduct, and granite or gneiss for the longest portions of the other three, changing to limestone on their approach to Lugdunum. In some places on the Gier aqueduct, sandstone, too, was used. Brick was used in leveling courses of the pillars and in the voussoirs of arches, as well as in the channels. The erosion of brick courses and elements is largely responsible for the poor state of preservation of parts of the Gier aqueduct. The cores of substructures, arches, *etc.* consisted of mortared rubble (Burdy 2002a: 79).

The free-surface channels were all built on the same basic principle: the vertical side walls were supported on a foundation of mortared rubble. The channel was covered by a barrel vault or, in the case of the Mont d'Or aqueduct, by a three-stepped corbelled vault. The Yzeron aqueduct was in portions covered by stone slabs. The interior surface was generally lined with plaster and one or two layers of *opus signinum* above a layer of mortared rubble (*opus caementitium*, total thickness 0.2-0.25 m). The vertical side walls were covered with a plaster lining, usually up to the arch springs of the barrel vault. The interior lining in the lower edges of the channel, where the horizontal and vertical surfaces met, was reinforced by an additional seam of *opus signinum*. The width of the channel varied between 0.27 m (some stretches of the Yzeron aqueduct) and 0.76 m (Brévenne), and the interior height from channel sole to the highest point of the intrados varied between 0.65 m (Mont d'Or, without the height of the corbelled vault) and 1.7 m (Brévenne). The Yzeron aqueduct has traces of two superimposed channels, the lower one filled up and the upper one built on top of it with a height increase of 0.22-0.4 m (Burdy 2002a: 81-3).

	Mont d’Or	Yzeron	Brévenne	Gier
length (km)	26	27 or 40	70	86
straight distance (km)	10	14 or 20	26	42
length/distance	2.6	*ca.* 2	2.7	2.05
elevation source (m)	372/311	600 or 710	627	405
elevation end (m)	260	268	282-284	299.5
head loss (m)	51	332 or 442	345-343	105
channel width (interior) :	0.5	0.40-0.55	0.55-0.75	0.55
height of channel side wall (m)	0.65	0.35-0.95	1.10-1.20	1.3
tunnels (number)	0	0	4 (?)	11
channel bridges (number)	3 or 4 (?)	0	3-6 (?)	40 (?)
walls and arches (number)	0	0	2	10
known man holes (number)	1	3 (?)	10	81 + 8
inverted siphons (number)	2	1 double	1 (+1?)	4
inverted siphons total length (km)	3.9	5.8	4	5.15
total head loss (m)	19	40	15 (?)	24.8
known drop shafts (number)	0	2 stairs	8	0 (?)
gradient of channel (/1000)	1.4	?	1.3-0.9	0.5-1.2
flow rate (cubic meters/day)	2,000-6,000	6,000	10,000	12,000

Table 9-1: Aqueducts at Lugdunum (Burdy 2002a: 14)

	length (m)	depth (m)	head loss (m)	hydraulic gradient (m/km)
Mont d’Or 1	420	30	8	19?
Mont d’Or 2	3,500	70	11	3.1
Yzeron 1	2,200	33	7	3.2
Yzeron 2	3,600	91	33	9.2
Brévenne 1	3,500	90	14/16	4/4.6
Brévenne 2	500?	20/22?	?	?
Gier 1	700	79	5.8	8.3
Gier 2	1,210	93.5	8.8	7.3
Gier 3	2,660	122.3	7.9	3
Gier 4	575	38?	2.3	4

Table 9-2: Inverted Siphons at Lugdunum (Burdy 2002a: 136)

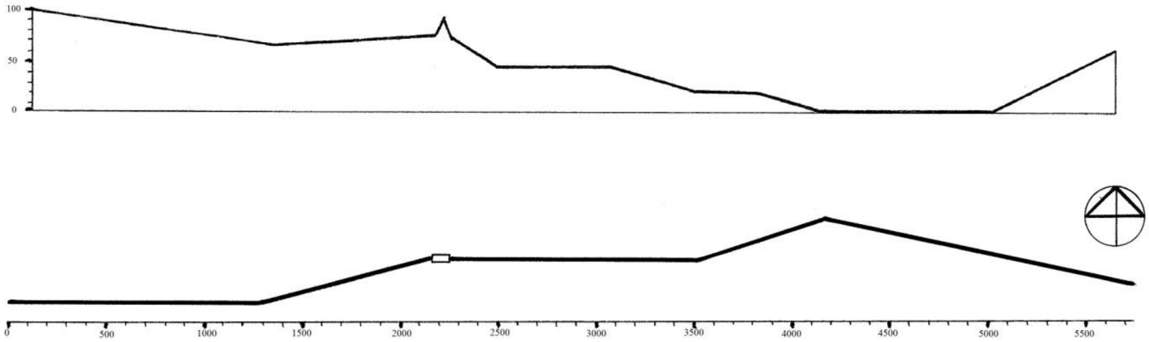

Figure 9.1: Evolved Elevation and Plan Pipeline Yzeron (Flow Direction Left to Right)

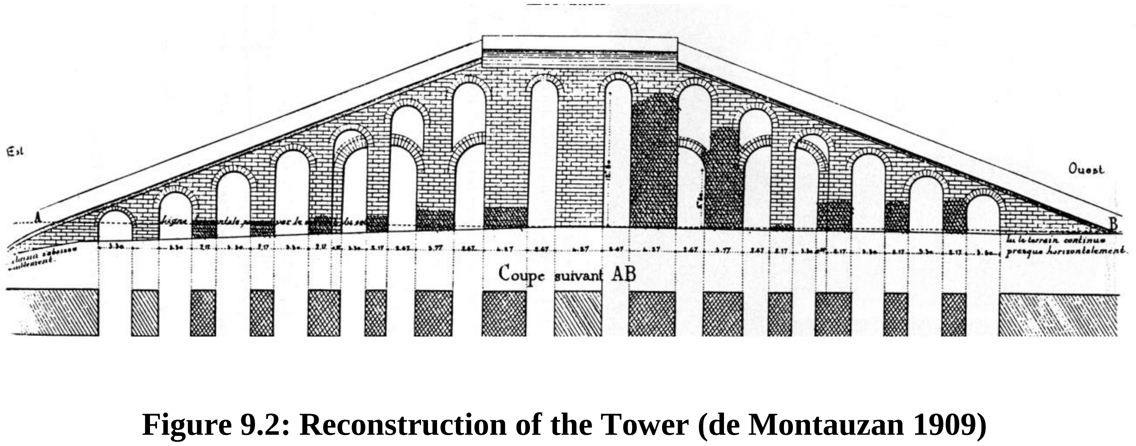

Figure 9.2: Reconstruction of the Tower (de Montauzan 1909)

10. Segóbriga

10.1 Location and Topography

The site of Segóbriga is located on a hill called Cabeza del Griego (“Head of the Greek”) (Appendix: Fig. 0.31). The name of the hill is perhaps the result of a corruption of *Graviega*, an alternative name of the ancient town of *Ercavica*, which some scholars have placed in the location that is now accepted as ancient Segóbriga (Hübner 1955: 397). Identification of the site of Segóbriga at Cabeza del Griego is now generally accepted on the basis of inscriptions (Schulten 1955: 1077), though some scholars recently still contested the identification on the basis of numismatic evidence (Villaronga Garriga 1978).

The site is located at 39°53′N latitude and 2°49′W longitude, 4 km south of the modern town of Saelices in the Spanish province of Cuenca, 100 km southeast of Madrid. The province of Cuenca is located in the east of the Autonomous Community of Castile-La Mancha. The top of Cabeza del Griego reaches 857 m a.s.l. On its steep south side the hill is protected by the Rio Gigüela. This stream serves as a natural trench, and runs 75 m below the top of Cabeza del Griego. The hilltop has an area of 10.5 ha, a size that is typical of a fortified Iron-Age settlement on the eastern Spanish plateau (Abascal, Almagro-Gorbea *et al.* 2005: 8). Gentle hills make up the undulating topography of the surrounding area. The region is at present under intensive agricultural use. The area around Saelices, where the Roman aqueduct had its origin, slopes gently downward from around 1000 m a.s.l. north of Saelices to roughly 800 m a.s.l. near the streambed of the

Gigüela at Segóbriga. Today the architectural remains of Segóbriga are protected by the Parque Arqueologico de Segóbriga.

Excavations in the 1980s revealed that the Roman city wall, built under Augustus, was 1.375 km long, surrounding a roughly square area of approximately 10.5 ha (Almagro-Gorbea 1989: 275). The architectural remains, among which there are at least two bath buildings, a theatre and an amphitheatre, indicate that in the Imperial Roman period it was an important city (Schulten 1955: 1077). All architectural remains that are visible today stand clustered along the north slope of Cabeza del Griego.

10.2 Climate

Since this part of Castile-La Mancha is not very densely populated, long-term climate data are difficult to obtain. The nearest stations for which data are easily available are Albacete (130 km southeast), Ciudad Real (140 km southwest), Madrid (100 km northwest), and Valencia (220 km east). The stations of Albacete and Ciudad Real provide no precipitation data.

Average temperature data for Albacete derived from GHCN 2 Beta, from 565 months between 1866 and 1948 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	5.1	6.5	9.5	11.4	15.3	20.9	24.5	23.9	20.8	14.8	9.8	6.3	14.2

Average temperature data for Ciudad Real derived from GHCN 1, from 116 months between 1981 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	5.9	7.8	10.9	12.5	16.5	22.1	26.0	25.5	22.2	15.9	10.5	6.8	15.4

Average temperature data for Madrid Barajas derived from GHCN 1, form 356 months between 1951 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	5.3	6.7	9.7	12.0	16.1	20.8	24.6	23.9	20.5	14.7	9.3	6.0	14.2

Average precipitation data for Madrid Barajas derived from GHCN 1, from 347 months between 1951 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	45.1	43.2	36.8	45.4	39.7	25.2	9.4	10.0	29.3	46.4	63.9	47.0	438.9

Average temperature data for Valencia derived from GHCN 1, from 295 months between 1951 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	10.9	11.6	13.4	15.1	18.3	21.5	24.4	24.8	22.7	18.7	14.4	11.7	17.4

Average precipitation data for Valencia derived from GHCN 1, from 666 months between 1861 and 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	32.3	30.2	33.8	35.2	34.8	22.4	8.6	14.8	63.8	96.3	53.5	41.5	468.7

Due to the inland location and the elevation of the stations, the climate data for Madrid and Ciudad Real are most likely to correspond with the situation at Saelices/Segóbriga. Madrid and Ciudad Real are located at elevations of 609 m and 628 m a.s.l. respectively, while Albacete and Valencia are located at 43 m and 13 m a.s.l., *i.e.* much lower than Segóbriga. Moreover, Valencia is situated directly at the Mediterranean Sea and is furthest away from Saelices/Segóbriga. The average annual temperature for Valencia (17.4 °C) is significantly higher than for the other three stations (14.2 °C, 15.4 °C, 14.2 °C for Albacete, Ciudad Real, and Madrid respectively), evidently due to the dampening effect that the Mediterranean Sea has on the winter temperatures. The coldest month in Valencia is January, at 10.9 °C; the coldest month, *e.g.*, in Albacete is January, at 5.9 °C. Therefore the data for Valencia should serve as comparative values only, as they probably do not reflect the situation at Segóbriga.

At Madrid, Ciudad Real, and Albacete, the annual average temperature is between 14.2 °C and 15.4 °C. The coldest month for all three stations is January, at 5.1 °C-5.9 °C. The hottest month in all three cases is July, at 24.5 °C-26.0 °C.

Precipitation data that appear relevant for Saelices are available only from Madrid. The average annual value is 438.9 mm. November is the wettest month with 63.9 mm, July the driest month with 9.4 mm. The climate is, therefore, typically Mediterranean, with hot, dry summers and mild, damp winters. It follows that in Madrid, on the long-term average, the months from June to September must be considered arid.

10.3 History

Nothing is known about the origin of Segóbriga (Abascal, Almagro-Gorbea *et al.* 2005: 9). Pliny the Elder calls Segóbriga *caput Celtiberiae* (*NH* 3.25). Strabo (3.4.13) and Ptolemy (2.6.57) also identify Segóbriga as a Celtiberian settlement. After the conquest by the Romans in the early second century B.C. Segóbriga probably became an *oppidum*. Although it is not specifically named in the sources, the city probably played a role in the Lusitanian War in the 140s B.C., during which Viriatus led the Lusitanians against the Romans (Appian, *Hisp*. 11.61-70), and in the Sertorian War (Appian, *Hisp*. 16.101). In the Augustan period Segóbriga probably became a *municipium*. Probably at the same time the city grew in importance through the mining industry. Pliny the Elder (*NH* 36.160) mentions the surroundings of Segóbriga as an important find spot of *lapis specularis*, a translucent form of gypsum that was commonly used as window pane or roof covering. The early Imperial period in Segóbriga is characterized by the construction of monumental buildings, reaching its climax under the Flavian emperors (Abascal, Almagro-Gorbea *et al.* 2005: 9).

The city continued to exist throughout the Imperial period, but during the early fourth century A.D. some of the buildings, such as the theater and the amphitheater, were gradually abandoned. This development is indicative of a general economic decline and gradual conversion to a primarily rural settlement. The construction of a large Visigothic basilica surrounded by an important necropolis shows that Segóbriga was still an important town in the sixth and seventh centuries A.D., albeit with a much reduced urban population (Abascal, Almagro-Gorbea *et al.* 2005: 9). There are no estimates of the population size of Segóbriga, though Almagro-Gorbea (1989: 279) calls the city “relativamente modesta” (relatively modest).

10.4 Economy and Communications

Economically Segóbriga was always an important center of agricultural production and raising of livestock. It was situated at the crossroads of important routes of communication (Abascal, Almagro-Gorbea *et al.* 2005: 9). The road from Complutum to Carthago Nova intersected here a road connecting the Ebro valley with Lusitania and a road from Toletum to Valeria (Abascal, Almagro Gorbea *et al.* 2006: 185). This information is at odds with the Barrington Atlas, which shows only a minor road coming from Saltigi in the south-east, and leading north from Segóbriga, ending nowhere (Talbert 2000: 27).

10.5 Bath Buildings

The city of Segóbriga had two bath buildings. The remains of the Augustan *termas del teatro* or *termas exteriores* (Theater Baths or Exterior Baths) were excavated just inside the city wall, immediately adjacent and architecturally joined to the theater by means of a cryptoporticus (Appendix: Fig. 0.35). The bath building is located at an elevation of 820 m a.s.l. (Abascal, Almagro-Gorbea *et al.* 2005: 16-7) and was part of an architectural and functional complex consisting of the theatre, the cryptoporticus, swimming pool (*natatio*), and a gymnasium. The ensemble of buildings was dedicated to the imperial cult, such as was common especially in the East and was supposed to introduce the local élites to Roman customs (Almagro Gorbea 1987: 213; Abascal, Almagro Gorbea *et al.* 2006: 190). The bath was of irregular plan, built in “Republican style” (Abascal, Almagro Gorbea *et al.* 2006: 190). The main *apodyterium* is relatively well preserved, with remains of a bench that ran around the walls, and a number of niches in the walls to hold the belongings of the bathers. From this room a door gave access to a similar room, perhaps the women’s *apodyterium.* During a site visit in the summer of 2006 it was not possible to procure information about the exact dimensions of the bath building. It is roughly rectangular and of relatively modest size (*ca.* 15 x 20 m).

The *termas monumentales* or *termas interiores* (Monumental Baths or Interior Baths) are located at the north-west side of Cabeza del Griego at an elevation of 830 m a.s.l., and were built in the late first century A.D. (Appendix: Fig. 0.36). The total area of the baths, including a *palaestra,* is 87.9 m x 39.1 m (300 x 132 Roman feet). The prominent position of the bath building above most of the other public buildings ensured unobstructed exposure to the sun for passive solar heating. The bath was of the linear type with the usual succession of *frigidarium* with *natatio*, *tepidarium,* and *caldarium*. Access to the bath was through the *palaestra* (29.25 m x 18.5 m; surrounded by colonnades) in the north-east. As was common, the *caldarium* was located in the south-west, to make use of passive solar energy (Abascal, Almagro-Gorbea *et al.* 2005: 26-8).

10.6 Water Supply System

As the Gigüela river runs some 70 m below the top of the hill, it was impractical to use its water to supply the city. At least five large cisterns scattered across the hilltop of Cabeza del Griego indicate that rain water run-off from roofs and streets was a major source of water for daily use (Appendix: Fig. 0.34). The cisterns are dated to the Roman period and were made of concrete with an interior lining of hydraulic plaster (*opus signinum*). It is unknown in what way exactly the cisterns were filled (Almagro Gorbea and Abascal Palazón 1999: 130). As in many other towns and cities under the Julio-Claudians, the water supply improved significantly with the building of an aqueduct under the emperor Claudius (Almagro-Gorbea 1989: 284). One of the cisterns, on the eastern slope of the hill, may have served as receiving tank for the inverted siphon that formed part of the aqueduct (Abascal, Almagro-Gorbea *et al.* 2005: 33).

Outside of Spain, little scholarly attention has been given to the aqueduct at Segóbriga. Part of it was first described by Mariano Sánchez Almonacid in a letter to the *Academia de la Historia*, dated 24 August 1876. The letter was published in 1889 (Sánchez Almonacid 1889: 878). A full description of the remains of the aqueduct, as well as an attempt at dating it were published only in the 1970s (Almagro Basch 1976, 1978). These publications remain the only works to date that are devoted entirely to the aqueduct. Neither Grewe (1984), nor Hodge (1992), nor Wikander (2000) mention the aqueduct of Segóbriga. Only Fernandez Casado (1983: 515-21) gives it a prominent place in the chapter on siphons in his monograph on Roman hydraulic technology. A site visit in the summer of 2006 as well as a comparison of diagrams published by Almagro Basch (1976) and Fernandez Casado (1983) with satellite images from Google Earth Plus revealed that the scale in all the publications is wrong by a factor of 2, *i.e.* all distances on the maps and diagrams must be divided by 2 to be correct. All distances in the description of the aqueduct below are, therefore, 50 % shorter than given in literature (Appendix: Fig. 0.29).

The source of the aqueduct lies just north of the modern city of Saelices at an elevation of 900 m a.s.l. (39º55’40”N latitude; 2°47’50”W longitude). The source consists of a main seepage gallery, roughly 110 m long, as well as four small side branches (Almagro Basch 1976). This gallery is a small-scale *qanat*, a technique that originated in ancient Persia. According to Hodge (2000c: 35) the *qanat* became common in Spain only with the arrival of the Moors, but at Segóbriga the technique was present already in the Roman period.

Today the *qanat* north of Saelices still supplies water to a fountain basin (Fig. 10.5). The *qanat* mouth and the basin were completely restored in 1997. Of the 14 manholes that had been originally sunk during the construction of the seepage gallery, five were visible to Almagro Basch (1976: 881). Of these all but the one nearest to the *qanat* mouth have been sealed with concrete, along with the mouth of the gallery (Fig. 10.3). Nevertheless, the positions of five of the manholes are clearly visible above ground. The manhole that is still accessible has a square cross-section with stepping holes in two opposite side walls that allow convenient, albeit precarious descent into the gallery below (Fig. 10.4). When Almagro Basch surveyed the aqueduct in the 1970s, he was able to walk most of the *qanat* underground (Almagro Basch 1976: 879).

The exact nature, shape, and size of the ancient collecting and distribution basin or *castellum* are unknown. In 1997 a new catchment basin was constructed, fed by the *qanat* through five water spouts built into a pediment. This source is known by the name Fuente de la Mar ("Mar Fountain"), probably derived from the Arabic word for water, *mayeh* (Almagro Basch 1976: 878). There are no estimates regarding the volume flow rate. Crude measurements conducted at Fuente de la Mar with an empty water bottle and a wristwatch in late June of 2006 (after a period of unseasonably strong rain) showed a flow rate of approximately 30 liters per minute or 1.8 cubic meters per hour.

In antiquity the water from the seepage gallery was supplemented by a true spring, today known as Fuente de las Zarzas ("Fountain of Brambles"), just east of Saelices (Fig. 10.6). This spring dried up and stopped flowing in the late nineteenth century (Almagro Gorbea and Abascal Palazón 1999: 131). Near the Fuente de las Zarzas, Almagro Basch excavated a 15 m long stretch of a channel that in his opinion served to hold a lead pipe and formed an inverted siphon. Further south, the channel was obliterated by erosion due to surface water. Moreover, the construction of the old road between Madrid and Valencia, the recent construction of the new highway, as well as intensive agricultural activity have cut and destroyed all traces of the aqueduct in this area (Almagro Basch 1976: 886). Along the stretch that is now destroyed a transition must have taken place from the inverted siphon to an open channel, since the traces of the aqueduct channel on the side of the cut opposite from the source are lined with fine hydraulic plaster (*opus signinum*) (Almagro Basch 1976: 887), indicating that the channel itself, and not a pipe, must have been the water conduit in this section. Such an interpretation is at odds to the information given by Fernandez-Casado (1983: 520), who clearly shows in a diagram that an open channel with free-surface flow ("zona canal"; "conducción rodada") ran all the way from the *qanat* to a point west of the estate "Los Vallejos", where the inverted siphon and the zone of pressurized flow began ("sifón"; "conducción forzada") (Appendix: Fig. 0.32).

A number of stretches of the channel were excavated along several stretches of its course ("en varios trechos de su trazado"). It was built of concrete—Almagro Basch (1976: 887) calls it *opus concretum cimenticium* [*sic.*]—on a foundation 0.3 to 0.4 m wide. The inside measurements of the channel are small (width between 0.12 m and 0.15 m; depth 0.2 m). Impressions in the top faces of the side walls as well as fragments around the channel show that it was covered by curved tiles (*imbrices*) (Almagro Basch 1976: 887).

At a point southwest of Los Vallejos, Almagro Basch revealed a rectangular reservoir or tank, 0.5 m x 0.7 m in size and 0.65 m deep, carved out of the bedrock. Cleaning of this tank revealed a piece of lead pipe underneath numerous fragments of *imbrices*. Since this interruption in the channel is located at a sharp drop in the terrain, it seems reasonable to assume that this reservoir served as a header tank for an inverted siphon. In this location the excavators also found a fragment of Hispanic *sigillata* embedded in the mortar that allowed them to date the aqueduct to the mid-first century A.D. (Almagro Basch 1976: 890).

Further south in the direction of Segóbriga more lead pipe fragments came to light near the course of the channel (Appendix: Fig. 0.33), confirming that the aqueduct designers had indeed used an inverted siphon to negotiate the extended dip in terrain along the last few kilometers between Los Vallejos and the north slope of the ancient city (Almagro Basch 1976: 891). The lead pipe fragments have a roughly circular cross-section with an approximate diameter of 0.1 m and a wall thickness of 0.02 to 0.03 m. The pipes consist of bent lead sheets soldered lengthwise (Almagro Basch 1976: 893), the typical Roman manufacturing technique.

Due to extensive agricultural activity in the area south of Saelices, Almagro Basch was able to follow the course of the aqueduct to Segóbriga only in stretches. Long sections of the inverted siphon in particular are conjectural or based on tenuous evidence (Almagro Basch 1976: 891-92).

The total length of the aqueduct from Fuente de la Mar to Segóbriga is *ca.* 7 km. The inverted siphon as restored would have been 2.5 km long. The presumed position of the header tank, just west of Los Vallejos, lies on a hill at an altitude of 870 m a.s.l. From here, the pipeline turned south, running steeply downhill at a right angle with the contour lines for about 150 m. Skirting the east side of a hill near La Pinilla, the inverted siphon reached its first low point at the intersection with the modern road between Saelices and Quintanar de la Orden, at 820 m a.s.l. From here, the pipeline seems to have run southeast, ascending to 840 m a.s.l. at Camino de Medina, the first high point. The pipeline then turned southwest for 250 m and descended again to its absolute low point at 800 m a.s.l., where its route intersects the modern road to Almonacid del Marquesado. Maintaining the same general direction for 150 m, the pipeline ascended again to a second intermediate hill at an elevation of 832 m a.s.l. From here, the pipeline ran for 300 m in a smooth arc, turning almost straight south to a third low point at an elevation of 810 m a.s.l., 50 m north of the remains of the ancient theatre. From this point, the pipeline must have run the last 100 m steeply uphill to the ancient city (Fernandez-Casado 1983: 520). The end point of the inverted siphon was most likely near the *termas exteriores* or *termas monumentales,* built at the end of the first century A. D. (Almagro Basch 1976: 893), *i.e.* after the presumed construction date of the aqueduct (mid-first century A. D., *cf.* above). This bath building is located at an elevation of 830 m a.s.l. (Fernandez-Casado 1983: 520). The location of the receiving tank of the inverted siphon near this bath building makes sense for two reasons. First, the *termas exteriores* were the biggest consumer of water in the city. Therefore, it makes sense to build the bath as close as possible to the end point of the aqueduct. Secondly, the baths—and, by extension, the receiving tank—are located close to the highest point of Cabeza del Griego, above all other structures in the city. Therefore, it would have been easy to distribute water (both fresh water from the aqueduct, and grey water from the baths) by gravity flow from here to every location in the city.

Therefore, assuming that the interpretation of the archaeological remains is correct, this inverted siphon has not only one but two intermediate high points, and a maximum drop of 70 m between the header tank and the lowest point along the line. The aqueduct route, however, is based on conjecture. The intermediate high points are caused by the generally undulating terrain and could not have been avoided except by a very circuitous route. A relatively straight aqueduct was certainly the more economical solution, despite the occasional high point.

During a site visit in the summer of 2006 it was not possible to find any evidence of the aqueduct except the sealed manholes of the seepage gallery and its new collection basin, an exposed stretch of aqueduct within the confines of the archaeological park (Fig. 10.8), and a 5 m stretch of channel on the surface between Los Terrenos and Los Vallejos. A large section of the aqueduct, nearly 200 m long, was obliterated with the construction of the highway between Madrid and Valencia immediately to the south of Saelices. The construction of this highway has completely changed the topography as well as the course of streets and roads in the area in question. Therefore it is necessary to produce an updated topographic map with the location of the aqueduct marked in relation to the structures built since the 1970s.

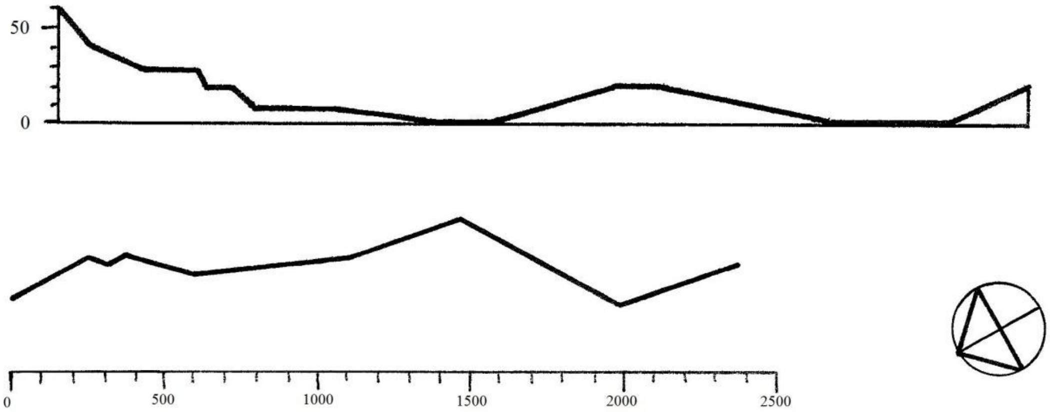

Figure 10.1: Evolved Elevation and Plan Pipeline Segóbriga (Flow Direction Left to Right)

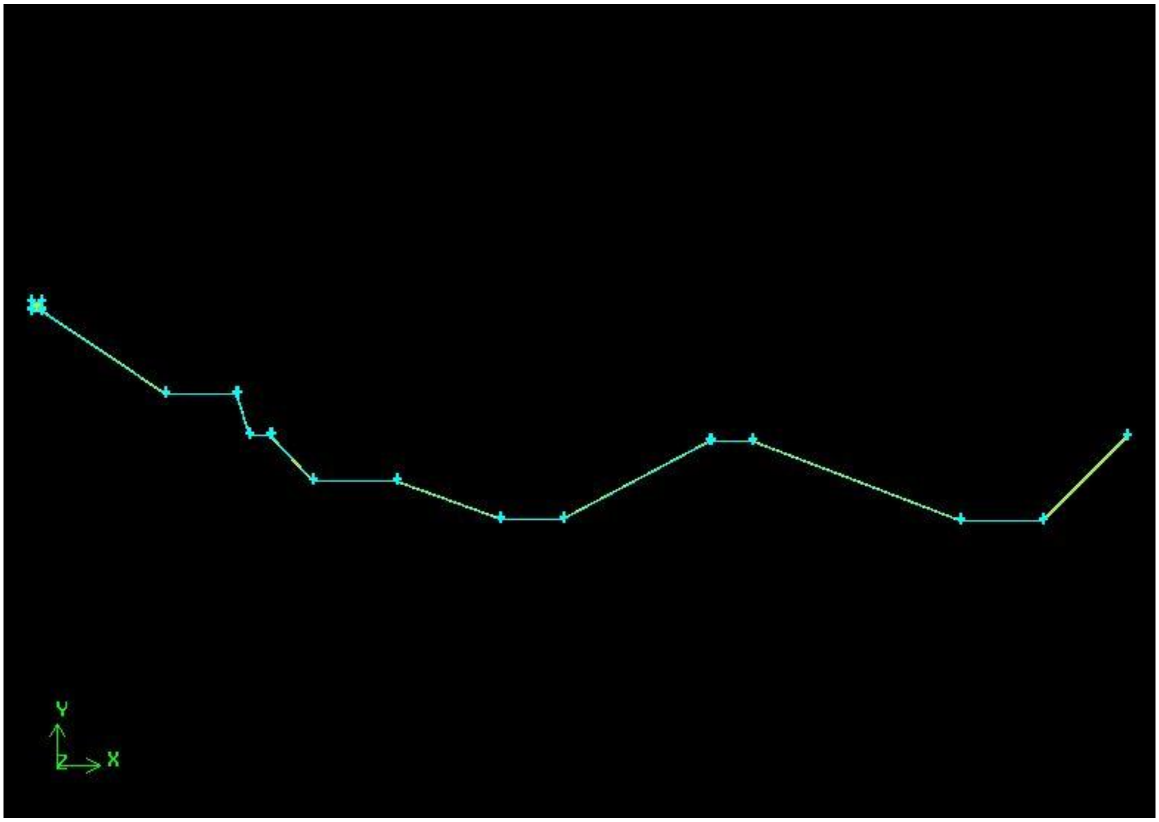

Figure 10.2: Segóbriga 2D Geometry in Reduced Scale

Figure 10.3: Manhole of *qanat* North of Saelices

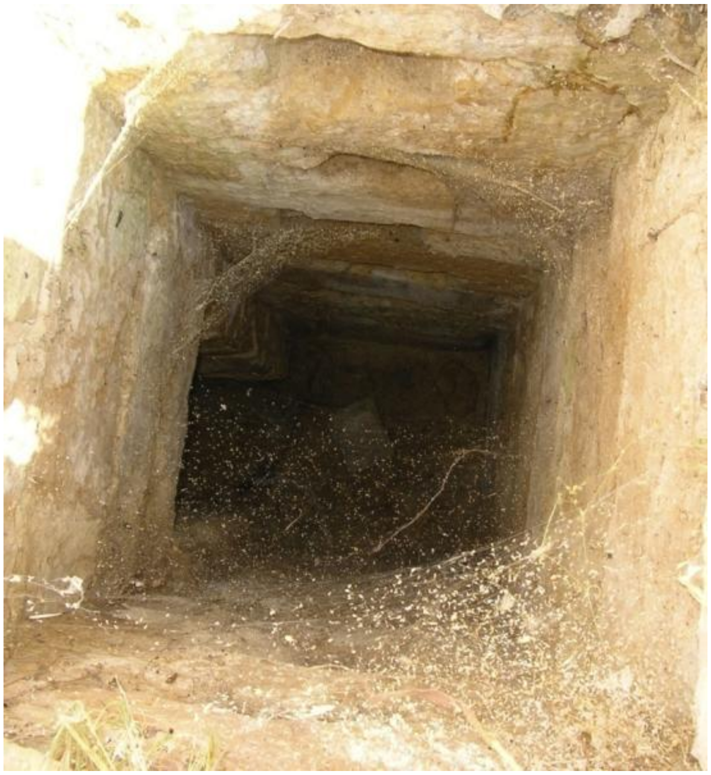

Figure 10.4: Interior of the only unsealed manhole

Figure 10.5 : Fuente de la Mar

Figure 10.6 : Fuente de las Zarzas

Figure 10.7: View of Segóbriga from the North

Figure 10.8: Exposed aqueduct channel in the Parque Arqueologico at Segóbriga

11. Aspendos

11.1 Location

The ancient city of Aspendos is located in southern Turkey at 36°56′N latitude and 31°10′E longitude, near the modern village of Belkis. It lies on the right, western bank of the Eurymedon River, today called Köprüçay, 13 km inland from the Pamphylian coast. Although the city had no immediate access to the Mediterranean, water transport from the sea to the city was possible up the Eurymedon River (Akurgal 1990: 333).

The site of Aspendos is largely unexcavated. The citadel is located on an oval, flat-topped hill about 0.24 km² in size, 60 m above sea level (Appendix: Fig. 0.37). It rises very conspicuously 30 m above the surrounding coastal plain. The slopes of the hill are steep, except for two locations, one on the east side and one in the north, where gates were located that gave access to the citadel. The mountains in the north, which form the westernmost edge of the Taurus Mountains, are 1.5 km from Aspendos.

11.2 Climate

Modern climate data for the nearby city of Antalya are readily available. According to these data the long-term average annual precipitation is 1051.9 mm. For comparison, this value is higher than the average value for the International Airport at Victoria, BC with 844.9 mm. The comparable value for Atatürk Airport in Istanbul is 624.1 mm. The driest month is August with an average of 2.0 mm, and the wettest month is December with almost 255 mm.

Precipitation Data, average 1929 – 1990 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	248.3	170.7	97.0	43.0	29.3	9.0	2.3	2.0	12.6	64.9	117.9	254.9	1051.9

The average annual temperature at Antalya is 18.4°. The coolest month is January with just below 10°, and the hottest month is July with just above 28°.

Temperature Data, average 1930 – 1991 (Hoare 2006):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	9.9	10.4	12.6	16.2	20.3	25.0	28.1	27.9	24.6	19.9	15.1	11.5	18.4

It follows that in Antalya, in the long-term average, the months from May to September must be considered arid.

11.3 Communications

The *Tabula Peutingeriana* shows that the coastal road from Attaleia (modern Antalya) through Perge to Side and on to Coracesium (modern Alanya) crossed the Eurymedon at Aspendos. Ward-Perkins (1955: 115) states that the city's location is the lowest practicable river crossing for all land traffic between eastern and western Pamphylia.

11.4 History

According to Strabo (14.4.2) Aspendos was founded by Argives, and inscriptions indicate that the city was founded by Achaeans in the Mycenaean period (Jameson 1970: 99). The name Aspendos is not Greek in origin. Its early name appears on coins as *Estwediiys*, which likely derives from Asitawandas, a descendant of Mopsos mentioned in a Hittite inscription from near Adana, who is said to have settled Pamphylia together with Calchas and Amphilochos after the Trojan War (Bean 1976: 101).

The Persian army and fleet assembled at Aspendos and were defeated by the Athenians under Cimon in 469 B.C. in the Battle of the Eurymedon. Aspendos appears on the tribute list for the Delian Confederacy in 425 B.C., but there is no evidence that the city ever paid tribute. In 411 B.C. the Persians used Aspendos as a base (Bean 1976: 102).

After the death of Alexander the Great the city was claimed both by the Seleucids and by the Ptolemies. Later, Aspendos was under the control of Antiochus the Great, and after the Battle of Magnesia, it came under Pergamene power. In 133 B.C., along with Pergamum, Aspendos was bequeathed to Rome, belonged in 102 B.C. to the *provincia Cilicia*, formed during Rome's fight against pirates, and to the province of Asia in 43 B.C. Mark Antony seems to have left this part of Asia Minor to Amyntas after the Civil War. The arrangement was confirmed by Augustus. In 25 B.C. the city belonged to the province Pamphylia (Jameson 1970: 100-1).

11.5 Population and Economy

An estimate of the population size of Aspendos is difficult. According to Lanckoronski's plan (1890), the city covered an area of 24 ha. The Roman theatre from the second century A.D. could seat 7000 spectators (Jameson 1970: 102). In 218 B.C., Aspendos could supply 4000 armed men (Polybius, 5.73.3-4). Under the assumption that half the population was male and that perhaps one third of the males were eligible to join armed troops, this would mean that the city may have had between 20,000 and 30,000 inhabitants in the late third century B.C. Strabo (14.4.2) calls Aspendos a well-peopled city.

Aspendos began to issue silver coins in the fifth century B.C., and until the fourth century the coins had a Pamphylian legend (Jameson 1970: 102). Olives were grown in the hills around Aspendos (Strabo, 12.7.1), and salt from a lake in the city's territory was probably another important commodity (Plin. *NH* 31.39).

The surviving architectural remains of Aspendos all belong to the Imperial Roman period. In addition to the unique aqueduct, the city is famous for its very well preserved theater, dating to the second century A.D. (Lanckoronski 1890: 102). It is situated with its *cavea* towards the outer face of the east part of the hill, and, as already mentioned, could hold approximately 7,000 spectators (Jameson 1970: 101). Its subsequent use as a Seljuk caravanserai is the reason for the excellent state of preservation. Other surviving buildings on top of the hill include a basilica on the east side of the *agora*, a two-storied market hall, and a nymphaeum (Bean 1976: 102). A recess in the back wall of the nymphaeum approximately 5 m above ground, running from the right side to a central niche is the probable location of a water conduit that was supplied by the aqueduct (Kessener and Piras 1997: 180, fig. 14). At the bottom of the central niche two perforated stone blocks forming 90°-joints with a bore of 0.25 m indicate that water arrived here under pressure (Kessener and Piras 1998b: 258).

11.6 Water Supply

How the inhabitants of Aspendos got their water before the construction of the aqueduct is unclear. They may have made use of wells in the plain below as well as of cisterns on the plateau (Ward-Perkins 1955: 115). Bean (1976: 103) suggests that "perhaps the river sufficed."

Thanks to the work done by Paul Kessener and Susanna Piras, the physical remains of the inverted siphon at Aspendos are very well documented (Appendix: Fig. 0.38). In two campaigns in 1996 and 1998 Kessener and Piras (2000b) surveyed the inverted siphon and traced the supplying aqueduct back to its two sources. Prior to their work the Aspendos aqueduct had been described by Niemann (Lanckoronski 1890) and by Ward-Perkins (1955). Ward-Perkins (1955: 122) gives the outside limits for dating the aqueduct as mid-second to end of third century A.D., corresponding to the approximate construction date of the nymphaeum on the plateau. An inscription (*IGRP* 804), dated to the second century A.D., mentions the donation of two million *denarii* by a certain Tiberius Claudius Italicus for the construction of an aqueduct at Aspendos. The current whereabouts of the inscription are not known. (Kessener and Piras 1998b: 105; Kessener 2000a: 256).

The distinctive inverted siphon with its two towers (Fig. 11.3), one of the great tourist attractions of the site, is merely a small part of the water supply system of Aspendos. The system delivered water through open channels from two springs into the header tank feeding the inverted siphon. The first spring is situated near the modern village of Gökçepınar (“heavenly spring”) at 550 m a.s.l., 15 km north of Aspendos. In April 1998 the flow rate of this spring was 30-40 liters per second (Kessener and Piras 2000: 264).

The total length of the aqueduct before the pressurized section is 19 km. Near the springs the aqueduct channel has disappeared, but at a distance of *ca.* 900 m, part of the channel several tens of meters long is visible before it disappears again. The channel at this stretch had an internal width of 0.6 m, side walls 0.4 m thick and 0.95 m high inside from the channel floor to the beginning of the vaulting. Further along the supposed course of the aqueduct two shafts, 1,200 m apart, one round with a diameter of 2.7 m, the other rectangular 2.7 x 2.7 m, indicate that the aqueduct must have run through two tunnels for part of its course. No tunnel entrances, exits, nor traces of a channel between the supposed tunnels remain (Kessener and Piras 2000: 264).

From here the aqueduct descended towards the second spring, Pınarbaşı (“fountainhead”), located at an elevation of 440 m a.s.l. The discharge measured at this spring is 40 l/s. Therefore both springs combined have a flow rate of 70 to 80 l/s with some annual variation that the authors leave unspecified. At the time the measurement was taken, the flow was neither at a high, nor a low extreme (Kessener and Piras 2000: 264).

From the point where the waters from the two springs mingled the aqueduct channel had a gradient of 16 to 17 %. 120 m down slope from the juncture, erosion from a mountain stream has cleared some of the debris that covered the channel and reveals the channel floor, covered at this point with a layer of concretion 0.3 m thick, with individual layers of more than five millimeters thickness. At this location the channel had a width of 0.55 m and a gradient of 8.5 % (Kessener and Piras 2000: 265).

Further down slope the aqueduct crossed the Kısık Dere gorge on a poorly preserved two-tiered bridge that originally was over 125 m long and 20 m high. After leaving the gorge the channel turned towards higher ground and ran through a tunnel again for several hundred meters. Once more a vertical shaft indicates the trajectory of the tunnel. The aqueduct then continues through an area where erosion has been less prominent, and, therefore, the channel is visible over a number of stretches, partly *in situ*, partly in eroded and collapsed state down the slope. The aqueduct negotiated two more depressions by running across bridges respectively 23 m and over 50 m in length, and passed through two more relatively short tunnels. Finally, for the last 3 km, the channel ran in a southerly direction with a modest gradient of 0.5 % towards the header tank of the inverted siphon (Kessener and Piras 2000: 265).

Since the hill on which Aspendos was located is separated from the mountains in the north by a stretch of the coastal plain that is 1.5 km wide, supplying the citadel with water required some technical effort. The distance to these mountains was too long to be bridged by an open-channel aqueduct (Kessener 2000a: 104). For this reason the designers chose to convey the water across the final two kilometers by means of a pipeline.

The bridges and towers of the pressurized section of the aqueduct were built of stones quarried locally in the mountains north of the pipeline, with a core of mortared rubble (Kessener and Piras 1998c: 214). Ward-Perkins (1955: 119) describes the material as “the local conglomerate, a very coarse stone.” The upper parts of the towers, beginning at an elevation of 15-17 m above ground, are built of brick. Lanckoronski (1890: 124) identified the brick part as a later restoration of the structure. Ward-Perkins (1955: 121), however, showed that the part built of brick is contemporary with the structure built of stone-faced mortared rubble.

From the header tank (Appendix: Fig. 0.39), the water was discharged into a single pipeline forming the first inverted siphon and descended 46 m of vertical distance. The downward gradient makes use of the natural slope of the hill on which the header tank was located. The first horizontal stretch is slightly curved and runs in part on top of a one-tiered arch-supported bridge (80 m long, 5 m high, 2.4 m wide). As the terrain rises slightly in the direction of the aqueduct, the substructure continues as a mortared rubble wall, which decreases in height with the rising ground. After this first stretch, the pipeline ascended the north tower to a height of about 40 m above the mentioned horizontal line. The horizontal distance from the header tank to the center line of the north tower is 592 m (Kessener 2000a: 116-17). The total pipe length between header tank and north tower was 613 m (Nikolic 2003: appendix p. 6).

At the north tower the pipeline changed direction by 16° towards the south and descended a vertical distance of 42 m to a second horizontal stretch. The water then flowed to the south tower, where it rose again to a height of about 37 m. The total pipe length between the north tower and the south tower was about 943 m (Nikolic 2003: 107). Kessener and Piras (1997: 161) and Lanckoronski (1890: 121) report a distance of 924 m from top to top of the two towers. The main bridge across the plain is 5.5 m wide and stands 15 m high above ground at the deepest point of the valley on arches, of which 29 were intact in the late nineteenth century. Ward-Perkins (1955: 119) presumed that it served also as a road bridge, although it is not immediately clear why there should be a bridge between the two towers for purposes other than carrying the pipe and occasional access for maintenance and repair crews.

At the south tower, the line changed direction by 55° to a bearing of 225º. It descended by roughly 23 m vertical distance to a third horizontal segment. This segment consisted of a two-tiered arched bridge with its upper level 17 m higher than the top of the main horizontal stretch between the two towers (Kessener and Piras 1997: note 22). Of this final bridge the remains of fourteen piers are visible, but only one of the arches is intact today. Where the bridge approaches the slope of the plateau, it was only one-tiered, as the ground rises. From here the pipeline ascended a vertical distance of 17 m to the receiving tank on the acropolis. The pipe length between the south tower and receiving tank was about 160 m. The combined distance of the three individual stretches was 1,670 m (154 m + 924 m + 592 m) (Kessener and Piras 1997: 166). The header tank and the receiving tank, as well as the water basins on top of the north and south towers, were open to the atmosphere (Kessener 2000a: 118). The figures for distances and heights are not quite accurate, since the authors give only straight horizontal distances and ignore the increased pipe length due to the curvature of the first horizontal line segment between header tank and north tower, and due to the ramp slopes. The elevation diagram (Kessener 2000a: 117, fig. 20) is awkward and not very helpful in the reconstruction of detailed values as the diagram does not use elevations above sea level but employs both the elevation of the header tank and the elevation of the long main horizontal line segment as datum levels. In addition, it is difficult to determine the gradient of the inclined pipe sections from the diagram supplied by Kessener (2000a: 117, fig. 19). The true pipe length as reconstructed from the diagram is 1,728 m (Nikolic 2003: appendix, p. 6).

Kessener and Piras (2000: 266, and 273, fig. 7) argue very convincingly that the designers of the pipeline chose the unusual course with two sharp bends for the pipeline for reasons of economy and safety. The executed layout represents, on the one hand, the variant with the shortest possible bridges. On the other hand it allows the pipeline to descend from the mountains and to ascend to the acropolis by crossing the topographical contour lines at right angles. Such a layout eliminates the need for lateral anchoring of the pipeline against slippage and erosion, which would be a great problem if the pipeline were to cross the contour lines at an oblique angle.

Kessener and Piras have identified the location and approximate size of both header and receiving tanks. The header tank is located some 600 m north of the northern tower on the southern edge of the first hill leading into the mountains at an elevation of

80 m a.s.l., and 50 m above the plain to the south. All that is left are two parallel walls running north-south, one meter wide, one meter high, and 2.5 m long (Appendix: Fig. 0.39). There is indication that the two walls were connected at their respective ends to form a rectangular basin. Its surface area must have been 2.7 m in N-S direction by 2.65 m in E-W direction. A square opening 0.3 m by 0.3 m in size and encrusted in a one-centimeter-thick layer of sinter on the current ground level in the western wall of the tank seems to have served as an overflow orifice. Slabs of *opus signinum* with layers of sinter up to one centimeter thick were evident on the nearby agricultural field. The open channel leading into the tank had been removed by the local farmers at some time in the past because it interfered with cultivation (Kessener and Piras 1997: 165-66).

The authors give no information about the likely maximal water level in the tank, which would be equivalent to the vertical distance between the tank bottom and the bottom of the overflow orifice. There is also no information about the height of the pipe outlet from the header tank into the first segment of the inverted siphon, as this outlet would have been in the southern wall, of which no traces are left (Kessener and Piras 1997: 183, fig. 20).

The two towers are almost identical, except for the change in direction (55° at the south tower, 16° at the north tower). At present, the remains stand roughly 30 m above ground, but originally they must have been significantly higher in order to reach the level of the hydraulic gradient. From these considerations their height must be reconstructed to

46 m for the north tower, and 32 m for the south tower (Kessener 2000a: 113 and 117, fig. 20).

Both towers are built to half their height of dressed stone, the “local conglomerate,” with a core of mortared rubble. At a height of 15 to 17 m above ground the building material changes to brick of very good quality with mortar layers of one to two centimeters thickness in between. The central section of each tower is square in cross-section (3 x 3 m). The central sections in both towers are oriented in a way that their centre line halves the angle of the pipeline’s change in direction (Appendix: Fig. 0.40). The interior is accessible through a door near the ground, and has a spiral staircase around a square pillar that in both towers is intact up to the top of the stone-built section, *i.e.* 17 m high (Kessener and Piras 1997: 161).

The inside surfaces of the intact brick walls show vestiges of a number of ascending brick vaults, three to a side. Thus a “sequence of brick vaulting spiraled upward, on top of which the staircase was made to continue in the brick part of the towers” (Kessener and Piras 1997: 162, and 177 figs. 7 and 8). The towers were, therefore, accessible all the way to the top. No *opus signinum* or any other evidence of a water basin is visible in either of the towers. But a layer of incrustation on the inside of the south tower indicates that water must have spilled down for a prolonged period of time (Kessener and Piras 1997: 162). The association of the towers with Vitruvius’ *colliviaria* (*De architectura* 8.6) is discussed elsewhere in this work.

Kessener and Piras (1997: 164) identified the remains of the receiving tank at the northern edge of the citadel, 154 m southeast of the southern tower. The substantial remains of a large pier are visible on the plateau, 15 m from the edge, in line with the final aqueduct bridge. This structure was built of mortared rubble with a facing of dressed stone. At present, the remains stand 4.5 m high and have a rectangular cross-sectional area of 1.8 x 2.35 m. The remains of an arch pointing in the direction of the south tower are visible at the side of the pier that faces the edge (Kessener and Piras 1997: 179, fig. 12). Originally this arch will have carried a horizontal conduit that must have been connected with the ascending branch of the final stretch of the pressure line.

A second extension in the form of an arch points away from the pier towards the south-west, at 90° to the first extension. It follows the course that Lanckoronski (Kessener and Piras 1997: 173, fig. 1) indicated on his map for the aqueduct on top of the plateau. The receiving tank probably discharged across this second extension into an open channel. The remains of this second arched extension allow a reconstruction of the floor of this channel at approximately 3 m above the highest ground level on the citadel, 6 m above the present top of the southern tower. Further remains of subsequent piers along the line indicated by Lanckoronski support this interpretation. Since the reconstructed level of this open channel is 0.5 m above the level of the horizontal recess in the back wall of the nymphaeum, it is likely that the large pier near the edge of the plateau was indeed the receiving tank of the inverted siphon (Kessener and Piras 1997: 164-65).

The pipe itself consisted of limestone blocks quarried locally at the foot of the Zincirli Mountains, which lies to the east, just across the Eurymedon. The individual stone pipe blocks measured between 86 x 86 x 50 cm and 90 x 90 x 70 cm, and have a bore of 28-30 cm (Kessener and Piras 1998a: 152). Although no pipe segments are left *in situ*, about 250 of them have been found built as *spolia* into a nearby Seljuk road bridge, where they were reused as readily available and precisely worked building material after the aqueduct had fallen out of use (Kessener and Piras 1998a; Grewe, Kessener *et al.* 1999; Harmeling, Stitz *et al.* 1999; Kessener 2000a: 266). More blocks were used as building blocks in nearby farmhouses or were scattered on the ground around the inverted siphon (Kessener and Piras 1997: 169).

Some of the stone blocks have a funnel-shaped opening in their side, perpendicular to the main bore (Kessener and Piras 1997: 169). Blocks with such orifices in their sides occur also at the inverted siphons of Smyrna (Weber 1899: 13), Laodicea ad Lycum (Weber 1898: 1), Patara (Stenton and Coulton 1986: 50-1), and Pergamum (Weber 1898: 6). The function of these side openings is unknown. Some of the openings were found with stone bungs *in situ* (Weber 1898: 6). Tölle-Kastenbein (1991: 29-30) states that they served to vent air bubbles from the pipeline and equates them to Vitruvius' *colliviaria*. Hodge (1992: 37-9) suggests they may have served as drains to empty the pipeline for maintenance and repairs. Stenton and Coulton suggest they may have been safety valves that were intended to blow open and thus save the pipeline from damage in case of pressure surges (Stenton and Coulton 1986: 50-1). Fahlbusch (1989) suggests that hot vinegar was poured through these holes into the pipeline for the chemical removal of calcium carbonate deposits from the inner pipe walls. None of these explanations seems universally satisfactory and applicable to all instances in which these holes occur. Equally dissatisfying are the attempts to explain the reason for the two towers. Most recently Kessener (2000a) suggested that they served to eliminate lateral forces that are generated by static water pressure at a depth of *ca.* 45 m below the level of the header tank. In physical terms this is what the towers do, but it is unclear if the designers built the towers with this function in mind. Anchors on ground level would have been sufficient to deal with the occurring forces. In the same publication Kessener asserts that water hammer must have occurred in the inverted siphon at Aspendos, caused by air bubbles escaping from the pipe. This assertion was seriously questioned by various scholars (Blackman and Peleg 2001). In Chapter 14 I deny the occurrence of water hammer in the inverted siphon at Aspendos as posited by Kessener. In Chapter 16 I suggest, instead, that the purpose of the towers was unrelated to hydraulics but was linked to the presence of stairwells within the central sections of the towers. Individuals had to be able to ascend the towers and to spend extended periods of time, perhaps several hours or up to several days, there. Access to drinking water must have been important for these individuals while they were at their elevated post. Guards protecting the otherwise vulnerable inverted siphon from manipulation are a possible example.

The Seljuk bridge across the Eurymedon River was documented by Lanckoronski (1890: 124), too, but he did not mention the perforated pipeline blocks. Detailed recent studies of the bridge and its relation to the aqueduct were published by Kessener and Piras (1998a), by Harmeling, Stitz and Mesenburg (1999) as well as by Grewe, Kessener, and Piras (1999). Surprisingly, pillar foundations of the bridge that date to the Roman period already contain pierced stone blocks from the aqueduct (Grewe, Kessener *et al.* 1999: 2). Their occurrence in the Roman bridge foundation can mean a number of things. It is possible that the reused stone pipe blocks did not pass the quality requirements during the construction of the aqueduct and were therefore utilized in a different structure. Perhaps they were damaged during manufacture or transport. Some of the blocks that were reused in the body of the Seljuk bridge, however, have thick layers of sinter in their bore (Grewe, Kessener *et al.* 1999: fig. 6). It is not known if the blocks that were reused in the Roman foundations also have this sinter accumulation. If they do, it could mean that the Romans reused in the bridge clogged stone blocks that they removed in the maintenance process from the aqueduct. Alternatively, the aqueduct may have fallen out of use quite early, namely in the Roman period. The traces of sinter in parts of the uncovered aqueduct channel indicate that this water supply system was probably in operation for at least 130 to 150 years (Kessener and Piras 2000: 267). It is possible that it was severely damaged or destroyed by an earthquake that was recorded at Cyprus in the year A.D. 363 (Grewe, Kessener *et al.* 1999: n. 14).

The volume flow rate of the Aspendos aqueduct has been estimated by Kessener to be 5,600 cubic meters per day or 65 liters per second (Kessener 2000a: 118). According to my calculations the volume flow rate was approximately 50 liters per second, similar to Kessener's result (Nikolic 2003: 58). These figures do not take into account variations in the discharge of the springs, but represent a maximal value computed from the bottom of the overflow orifice at the header tank and the position of the discharge opening from the receiving tank into the open channel on the acropolis.

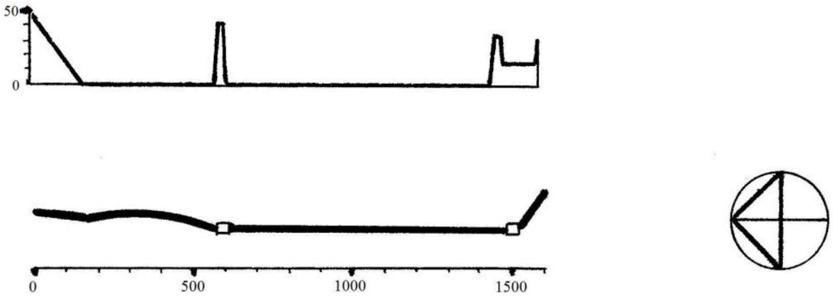

Figure 11.1: Evolved Elevation and Plan Pipeline Aspendos (Flow Direction Left to Right)

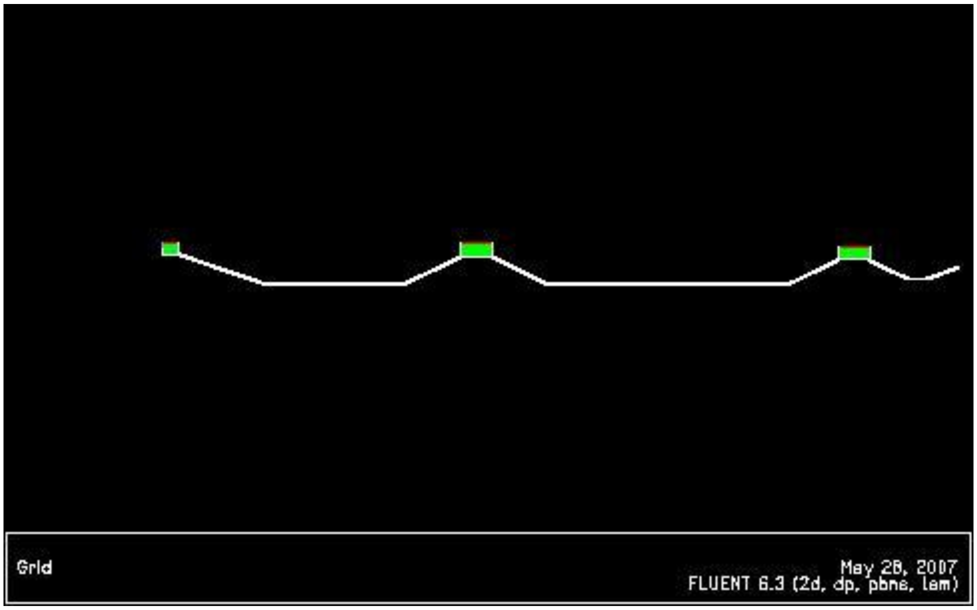

Figure 11.2: Aspendos Geometry in Reduced Scale

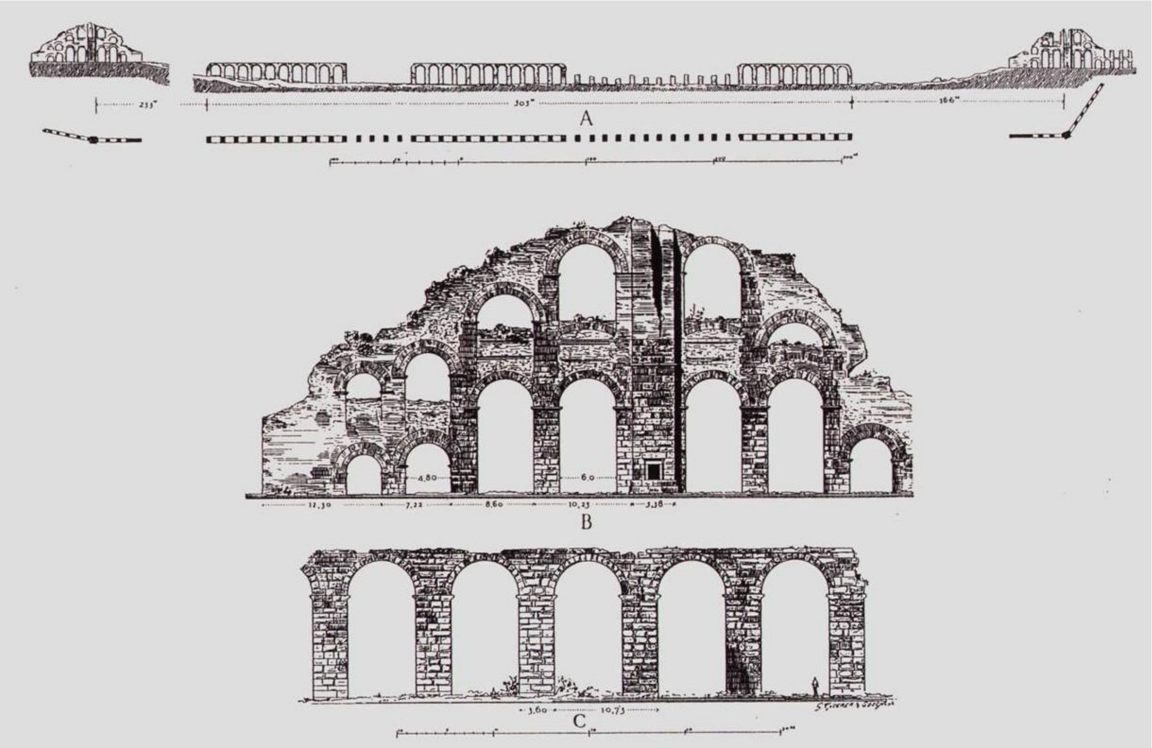

Figure 11.3: Plan and Elevation of Central Aqueduct Section and North Tower (Lanckoronski 1890)

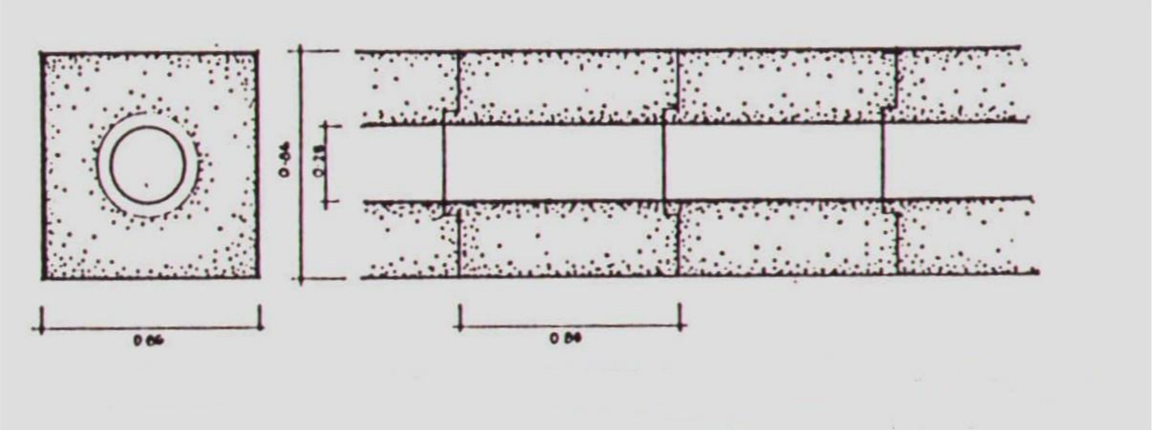

Figure 11.4: Pipe Segments (Lanckoronski 1890)

12. Key Data of Flow Regimes from Conventional Calculations

The exchange of scholarly articles by Kessener (2000a, 2002a), Blackman, and Peleg (2001) shows the need to determine beyond doubt what happens in an inverted siphon while it is initially filled with water (unsteady flow) and while it runs in normal operation (steady state condition). The discussion revolves around the presence and the effects of air in the pipeline. Two questions need answering: 1. How can air enter the pipeline? 2. What effects does air have if it is present in the pipeline? Kessener and Blackman, notably both engineers by profession, disagree on these questions. Kessener (2000a: 126-9) asserts that air pockets escaping through leaks in the pipeline cause water hammer, potentially destructive pressure waves. Blackman (Blackman and Peleg 2001: 411) denies the existence of air in the filled pipeline altogether. He is in agreement with Smith (1976: 57). In order to come closer to a resolution of this disagreement is necessary to determine the main flow properties, *i.e.* flow velocity and pressure at the lowest point of the inverted siphon. For the three systems at Yzeron, Pergamum, and Aspendos the steady-state flow properties have been determined and verified (Garbrecht 1978: 7; Kessener 2000a: 113; Burdy 2002a: 170; Nikolic 2003: 105-23). No such calculations exist for Alatri, Segóbriga and Smyrna.

The answer to the question about the presence of air in the pipeline appears trivial: initially the “empty” pipeline is in its entirety full of air. As water is slowly admitted into the pipe, the air is gradually displaced and escapes through openings (*i.e.* header tank, receiving tank, and intermediate tanks or lateral pipe openings) into the atmosphere. Since water is denser than air, water will flow to the bottom of the pipeline, where it will spread out horizontally and form a stratum above which the air is slowly pushed upward as the water level rises. The situation is equivalent to filling of an empty glass with water, albeit with a much more complex vessel geometry. The static interface between water and air is a horizontal layer. The air is displaced upwards as long as there is an opening through which it can escape. If the vessel is closed at its upper perimeter, the air cannot escape and forms a stationary bubble that will be compressed by the rising water until the internal pressure of the air bubble is equal to the static pressure of the water at the depth of the interface layer. This situation occurs in a diving bell, where an air bubble is enclosed by an overturned cavity. In pipelines the situation occurs if a local high point is situated between header and receiving tank without provision to vent the air bubble. Callebat (1973: 175) mentions "air emprisonné", imprisoned air.

It is important to emphasize that the air bubble will occur even if the apex of the high point is located below the line of the hydraulic gradient, contrary to Hodge's (1983: 198-9) statement that a so-called air lock will form only if the high point is located above the line of the hydraulic gradient. Erroneously, the associated schematic image of a pipeline (Hodge 1983: 200, fig. 8) shows a second local high point *below* the hydraulic gradient with *no* air lock. Archaeological evidence and inference from topography indicate that two ancient pipelines, at Lincoln (UK) and at Termini Imerese (Sicily), existed with intermediate high points *above* the hydraulic gradient. While this interpretation is doubtful for Termini Imerese (Balsamo 1958; Hodge 1983: 185; Belvedere 1986, 2000), the pipeline at Lincoln may have included a water lifting device that elevated the water above the level of the hydraulic gradient (Thompson 1954; Oleson 1984: 221-3).

Frequently the entrainment of air at the header tank is cited as the cause for air accumulation in the pipeline (Stehlin 1918: 170; Hodge 1983: 198; Lewis 1999: 166; Kessener 2001: 151; Burdy 2002b: 245; Kessener 2002b: 189; 2003: 154). This notion is based on a misunderstanding of the flow pattern during the filling of an inverted siphon. From everyday experience we are familiar with the cone of air forming in the center of the vortex of water when we pull the plug in the bathtub or the kitchen sink. Winkel (1914) and Knauss (1983) have investigated the influence of the depth of the drain below the water surface on the length of the resulting air cone. The phenomenon of air cones or bubbles entrained at the inflow of a pipe is, however, irrelevant to the filling process of ancient inverted siphons. When an empty vessel, be it a drinking glass or a U-shaped tube, is filled, the water level rises from the bottom to the top in the opposite direction of the inflow (Fig. 12.1). Where the inflow hits the level of rising water, the entrainment of air is stopped at a relatively shallow depth. The air will not be transported further down the pipeline, on the one hand because the air bubbles move upwards due to their buoyancy, on the other hand because during the filling of a U-shaped pipe the flow direction of the water in the full part of the pipe below the air-water interface is upward, too.

Figure 12.1: Air-Water Interface Moving Upwards in the Opposite Direction of the Inflowing Water (Nikolic 2003: 51, photo by J.W. Humphrey)

In the conventional curriculum of Fluid Mechanics courses pipe flow is a straightforward matter. A fundamental physical property in Fluid Mechanics is static pressure. If a diver is submerged in the sea, the weight of the water above him pushes down on his body. The deeper he dives, the more water is above him and the more pressure is exerted on him. If the water and the diver are at rest, the pressure exerted on the diver is known as *static* pressure. The same principle applies to water in a pipeline. For a fluid at rest, static pressure at any point in a pipeline is caused by the weight of water resting above that point. Regardless of the shape and diameter of the pipeline, static pressure depends only on the *vertical* distance between water surface and the point of interest. Static pressure is the same anywhere along a horizontal plane in the water. This applies also to a U-shaped tube. Due to static pressure, the fluid at rest always strives to reach equilibrium and, therefore, will move to the same level in both branches of the U-shaped tube, provided that both branches are open to the atmosphere. For a fluid at rest, static pressure at any point below the water surface is expressed as:

$$p_s = \rho g h \qquad \textbf{Equation 1}$$

p_s: pressure of water at rest (hydrostatic) in Pascal

g: gravitational acceleration $(9.81\frac{m}{s^2})$

h: depth of water above an arbitrary datum line in meters

ρ: density of water $(1000\frac{kg}{m^3})$

Conceptually the principle of hydrostatics was known to Archimedes. His first postulate about flotation expresses in prose what Equation 1 expresses mathematically:

> "We pose in principle that the nature of fluids is such that its parts being uniformly placed and continuous, that which is less pressed is displaced by the one which is pressed the more, and that each part is always pressed by the whole weight of the column perpendicularly above it, unless this fluid is enclosed someplace or is compressed by something else (Garbrecht 1987b: 15)."

As the passage demonstrates, all physical properties in Equation 1 were known to Archimedes at least intuitively, except for gravitational acceleration. Height can be measured easily by means of a ruler or measuring tape. Archimedes himself discovered the density of materials by his famous submersion experiment in which he tested the gold content of the crown of Hero II of Syracuse. In his postulate he also expresses the notion of parts pressing down on one another and the understanding that the bottommost part is subjected to the weight of all that is perpendicularly above. In mathematical terms, the equation, a multiplication of three factors, is not a difficult one. Two volumes on Greek mathematics in the Loeb Classical Library show that Greek philosophers were very adept at solving difficult geometric problems. After Alexander the Great, a great number of mathematicians from India, Persia, Syria, Asia Minor, and Egypt went to study and work at the courts of the Successor Kings, at Alexandria in particular (Cuomo 2001: 62), enriching further the tradition of Greek mathematics that had already flourished in Athens in the 5th and 4th centuries B.C. The problem with the mathematical expression of fluid mechanical phenomena in the ancient world is not a lack of skill at mathematics. A necessary step is the understanding that natural phenomena can be expressed in theory by using mathematical equations. This, too, the Greeks knew. Pythagoras, for example, related the pitch of musical scales in terms of mathematical relations (Kahn 2003: 1282). Ancient Greek astronomy, of course, made use of geometry, in its simplest terms attested in a text as early as Hesiod’s *Op.* 383. The inability to express fluid behavior in terms of mathematical equations lies partially in the difficulty of conceptualizing and determining physical constants such as gravitational acceleration (Landels 2000: 186), while the principle of gravity itself was well known, as Archimedes’ postulate above proves.

When flow takes place, the static pressure drops along the direction of the flow to compensate for shear or friction, *cf.* Equations 3-5. If one branch of the U-tube is lowered to below the water level, the equilibrium is disrupted. The column of water in one branch will be higher than in the other; the imbalance of pressure in the two branches causes the water to overflow from the lower branch. If, through supply of water from outside, the water level in the high branch is kept constantly above the level in the low branch, steady flow develops. The flow velocity of the water will depend entirely on the vertical distance between the water levels in the high and the low branch.

Generally the investigation of the flow regime in a pipe is limited to steady state operation. Water is an incompressible fluid because its volume does not change under the application of external pressure. Incompressibility makes the calculation relatively easy, because no changes in density need to be taken into account. In steady state operation the properties of the fluid do not change over time. Although the water is in motion, its measurable properties are always the same, no matter at which point in time they are measured. Two principles are relevant: conservation of mass and conservation of energy. The first principle states that the amount of water entering the pipe is the same as the amount leaving the pipe. The amount of water flowing through a pipe can be expressed as volume per unit time, measured in cubic meters per second. Volume flow rate can be visualized as a cylinder of water with a cross-sectional area equivalent to the cross-sectional area of the pipe and a height that is equivalent with the distance the water is moving per unit time, *i.e.* the flow velocity. The Law of Conservation of Mass states that the product of the flow velocity multiplied by the cross-sectional area of the pipe is equal everywhere in the pipe (Massey 1990: 74-5). In mathematical terms the Continuity Equation expresses this principle:

$$Q = u * A = const. \qquad \textbf{Equation 2}$$

Q: volume flow rate in cubic meters per second
u: flow velocity in meters per second
A: cross-sectional area of the pipe in square meters

Hero expresses this physical principle in *Dioptra* 31, where he suggests digging a pit of known size and measuring with a sundial how much of it the aqueduct fills in an hour:

> It is necessary to find the velocity of its current, because the more rapid the flow, the more water the spring will produce, and the slower it is, the less it will produce. (trans. Herschel)

The problem here is, of course, sufficiently small resolution in time measurement. The pit would have to be very large indeed to enable a measurement of filling time by means of a sundial. It appears unlikely that Hero's suggestion was put into practice in the prescribed manner. A water clock would be a more suitable instrument for time measurement that requires higher resolution. By comparing the amount of flow from a spring with the amount of flow from a water clock, even a type of flow calibration would be possible. This principle probably remained unnoticed by the Romans (Garbrecht 1987b: 17).

Frontinus knew that the amount of flow depended on the height at which a pipe was located beneath the water surface (*Aq.* 113), thereby combining on a cognitive level the information from Equations 1 and 2, and predating Torricelli's Law, $v = \sqrt{2 * g * h}$, by 1500 years. Although the Romans knew the implications of this principle from experience in dealing with their water supply system on a daily basis, they did not put it into mathematical terms. More precisely, the Romans expressed flow rate only in terms of cross-sectional area of the pipe, the *quinaria*. Flow velocity, the changes of which they recognized depended on the position of the pipe, did not enter their calculation (Hodge 1984: 206). The relation between flow velocity and cross-sectional area was discovered by Benedetto Castelli who published the *Mensuration of Running Water* in the early 17th century.

The Law of Conservation of Energy states that the energy of water flowing in a pipe cannot decrease but only be converted from one form to another. This principle is derived from the application to fluid flow of the First Law of Thermodynamics. In simplified terms energy exists in the form of velocity, of pressure, and of gravitational energy determined by the elevation above an arbitrary datum line. The sum of those three forms of energy is equal everywhere in the pipe (Massey 1990: 76-9). The phenomenon is known as Bernoulli's Principle, after Daniel Bernoulli (1700-1782). In mathematical terms for an incompressible medium such as water in steady flow Bernoulli's Equation reads:

$$E = \frac{u}{2}^{2} + g * h + \frac{p}{\rho} = const. \quad \textbf{Equation 3}$$

E: specific energy per kilogram of water

u: flow velocity in meter per second

In Equation 3, the first term expresses the kinetic energy contained in the flowing water, the second term expresses the potential energy due to the elevation of the water above the datum line, and the third term expresses the energy due to static pressure (Massey 1990: 79).

We find in Frontinus some of the principles expressed by Bernoulli’s Equation. Frontinus observed the kinetic energy of water in motion and preferred not to measure the flow in sections where water flowed more slowly: *huius mensuram ad caput invenire non potui, quoniam ex pluribus adquisitionibus constat et lenior rivum intrat*, “I could not take a measurement of this at the intake because it is made up of several intakes and enters the channel rather slowly,” (*Aq.* 70) or more impetuously: *cuius rei ratio est, quod vis quae rapacior, ut ex largo et celere flumine excepta, velocitate ipsa ampliat modum*, “The reason for this is that the swifter current, as it is taken from a large and rapidly flowing river, increases the volume by its very velocity,” (*Aq.* 73). Once again, the *aquarii* were familiar with this phenomenon through daily experience and observation, but they did not express it mathematically. Since their system of *quinaria* seems to have worked well enough for their purposes, there was no need to delve into the theory of flow phenomena. As practitioners, the Romans were interested in feasibility and practical application, not in pure knowledge, like the Greeks (Garbrecht 1987b: 17). I have already dealt with the second term, expressing potential energy, above in relation to Equation 1.

Bernoulli's Equation was derived using calculus, which was developed only in the late 17th century simultaneously by Newton and Leibnitz. Without such mathematical tools at their disposal, certainly also due to the unwieldiness of the Roman system of numerals, it was impossible to derive

Equation 3 is a simplified representation of reality and is valid only for frictionless flow. In reality, however, the water "particles" are rubbing against one another and against the pipe wall. Some of the total energy is, therefore, expended on overcoming this friction. An additional term expresses these energy losses:

$$E_f = \zeta * \frac{u^2}{2} \quad \textbf{Equation 4}$$

ζ: dimensionless head loss coefficient

In long, unobstructed pipelines of uniform diameter without built-in components, such as valves or sudden bends, the main cause of energy loss is fluid friction with the pipe wall. The French engineer Henri Darcy (1803-58) investigated the flow of water in pipes and developed the equation named after him (Massey 1990: 199-200):

$$E_f = h_f * g = \frac{fl}{d} * \frac{u^2}{2} \qquad \textbf{Equation 5}$$

f: dimensionless friction factor

l: pipe length in meters

d: pipe diameter in meters

Solving Equation 5 for h_f, gives the head loss due to friction.

$$h_f = \frac{fl}{d} * \frac{u^2}{2g} \qquad \textbf{Equation 6}$$

Under steady state conditions the head loss due to friction is exactly equal to the vertical distance between inflow and outflow. The friction factor *f* depends on the surface roughness of the pipe wall and a dimensionless parameter called the Reynolds Number. Since stone pipes and lead pipes are not commonly in use today, values for the wall roughness of heavily encrusted cast iron pipes, found in engineering tables (Gieck and Gieck 1990: Z9), sufficiently approximate the situation. The Reynolds Number is, in very simplified terms, a means of comparing similar flows with different geometries and different velocities. In pipe flow the Reynolds Number characterizes the flow regime: laminar, transitional, or turbulent. The Reynolds Number is determined by:

$$\mathrm{Re} = \frac{lu}{\nu} \qquad \textbf{Equation 7}$$

Re: Reynolds Number

v: kinematic viscosity of the fluid

A Reynolds Number above *ca.* 2,300 indicates turbulent flow. Below that value the flow is laminar. With the wall roughness and Reynolds Number in hand the value of the friction factor *f* is determined from a so-called Moody Chart that is commonly reproduced in most fluid-dynamics textbooks (Käppeli 1987: 125; Massey 1990: 205). With Equations 1-6 it is possible to determine the main flow properties.

12.1 Aspendos

Normal Operation

Flow Velocity and Volume Flow Rate

The distance between header tank and receiving tank is roughly 1,718 m:

$$l = 1718m$$

The pipe roughness is conservatively assumed as $k = 4mm$, a value taken from modern engineering tables for an encrusted cast iron pipe (Gieck and Gieck 1990: Z9):

$\therefore$ for pipe diameter 280 mm

$$\frac{k}{d} = \frac{4}{280} = 1.4 * 10^{-2}$$

$\therefore \lambda$ independent of Re $\rightarrow \lambda = 0.043$

Head loss due to pipe friction:

$$\Delta h_f = \lambda * \frac{l}{d} * \frac{u^2}{2g} = 0.043 * \frac{1718}{0.28} * \frac{u^2}{2 * 9.81 \frac{m}{s^2}} = 263.8 * \frac{u^2}{2 * 9.81 \frac{m}{s^2}}$$

For equilibrium conditions:

$$h = h_f$$

with $h = 15m$ (vertical difference in elevation between water levels in header and receiving tank), total head available must equal head loss:

$$15m = 263.8 * \frac{u^2}{2 * 9.81 \frac{m}{s^2}} = 13.4 \frac{s^2}{m} * u^2$$

$$\therefore u = \sqrt{\frac{15m}{13.4 \frac{s^2}{m}}} = 1.06 \frac{m}{s}$$

$$Q = u * A = u * \pi * \frac{d^2}{4} = 1.06 \frac{m}{s} * \pi * \frac{(0.28m)^2}{4} = 0.065 \frac{m^3}{s} = 65 \frac{l}{s}$$

Check for turbulence of flow with $\nu = 1.4 * 10^{-6} \frac{m^2}{s}$ for water at a temperature of 10ºC:

$\mathrm{Re} = \bar{u} * \frac{d}{\nu} = 1.06 \frac{m}{s} * \frac{0.28m}{1.4 * 10^{-6} \frac{m^2}{s}} = 212000 >> 2300$, therefore the flow is fully turbulent.

12.2 Yzeron

Normal Operation

Flow Velocity and Volume Flow Rate for One Single Pipe

Pipe length between header tank and receiving tank:

$l = 5800m$

The pipe roughness is conservatively assumed as $k = 4mm$, a value taken from modern engineering tables for an encrusted cast iron pipe (Gieck and Gieck 1990: Z9):

$\therefore$ for pipe diameter 180 mm

$$\frac{k}{d} = \frac{4}{180} = 2.2 * 10^{-2}$$

$\therefore \lambda$ independent of Re $\rightarrow \lambda = 0.05$

Head loss due to pipe friction:

$$h_f = \lambda * \frac{l}{d} * \frac{u^2}{2g} = 0.05 * \frac{5800}{0.18} * \frac{u^2}{2 * 9.81\frac{m}{s^2}} = 1611 * \frac{u^2}{2 * 9.81\frac{m}{s^2}}$$

For equilibrium conditions:

$h = h_f$

with $h = 40m$ (vertical difference in elevation between water levels in header tank and receiving tank), total head available must equal head loss:

$$40m = 1611 * \frac{u^2}{2 * 9.81\frac{m}{s^2}} = 82.1\frac{s^2}{m} * u^2$$

$$\therefore u = \sqrt{\frac{40m}{82.1\frac{s^2}{m}}} = 0.7\frac{m}{s}$$

$$Q = u * A = u * \pi * \frac{d^2}{4} = 0.7\frac{m}{s} * \pi * \frac{(0.18m)^2}{4} = 1.8 * 10^{-2}\frac{m^3}{s} = 18\frac{l}{s}$$

Check for turbulence of flow with $\nu = 1.4 * 10^{-6}\frac{m^2}{s}$ for water at a temperature of 10ºC:

$\mathrm{Re} = u * \frac{d}{\nu} = 0.7\frac{m}{s} * \frac{0.18m}{1.4 * 10^{-6}\frac{m^2}{s}} = 90000 >> 2300$, therefore the flow is fully turbulent.

12.3 Pergamum

Normal Operation

Flow Velocity and Volume Flow Rate

Section between header tank and receiving tank:

$l = 3470m$

The pipe roughness is conservatively assumed as $k = 4mm$, a value taken from modern engineering tables for an encrusted cast iron pipe (Gieck and Gieck 1990: Z9):

$\therefore$ for pipe diameter 220 mm

$$\frac{k}{d} = \frac{4}{220} = 1.8 * 10^{-2}$$

$\therefore \lambda = 0.045$ independent of Re

Head loss due to pipe friction:

$$\Delta h_f = \lambda * \frac{l}{d} * \frac{u^2}{2g} = 0.045 * \frac{3470}{0.22} * \frac{u^2}{2 * 9.81 \frac{m}{s^2}} = 709.8 * \frac{u^2}{2 * 9.81 \frac{m}{s^2}}$$

For equilibrium conditions:

$h = h_f$

with $h = 41m$ (vertical difference in elevation between water levels in header tank and receiving tank), total head available must equal head loss:

$$41m = 709.8 * \frac{u^2}{2 * 9.81 \frac{m}{s^2}} = 36.2 \frac{s^2}{m} * u^2$$

$$\therefore u = \sqrt{\frac{41m}{36.2 \frac{s^2}{m}}} = 1.06 \frac{m}{s}$$

$$Q = u * A = u * \pi * \frac{d^2}{4} = 1.06 \frac{m}{s} * \pi * \frac{(0.22m)^2}{4} = 0.04 \frac{m^3}{s} = 40 \frac{l}{s}$$

Check for turbulence of flow with $\nu = 1.4 * 10^{-6} \frac{m^2}{s}$ for water at a temperature of 10ºC:

$\mathrm{Re} = u * \frac{d}{\nu} = 1.06 \frac{m}{s} * \frac{0.22m}{1.4 * 10^{-6} \frac{m^2}{s}} = 166571 >> 2300$, therefore the flow is fully turbulent.

12.4 Alatri

Steady State Operation

Flow Velocity and Volume Flow Rate

The section between header tank and receiving tank has a length of roughly 3,300 m:

$l = 3300m$

As the pipeline layout is largely conjectural, nothing is known about sudden bends, sharp entries or exits. Therefore only friction losses are considered. The pipe roughness is conservatively assumed as $k = 4mm$, a value taken from modern engineering tables for an encrusted cast iron pipe (Gieck and Gieck 1990: Z9):

$\therefore$ for the smallest pipe diameter of 100 mm:

$$\frac{k}{d} = \frac{4}{100} = 4 * 10^{-2}$$

$\therefore f = 0.065$ is independent of the Reynolds Number (Gieck and Gieck 1990: Z8)

Head loss due to pipe friction:

$$h_f = f * \frac{l}{d} * \frac{u^2}{2g} = 0.065 * \frac{3300}{0.1} * \frac{u^2}{2 * 9.81 \frac{m}{s^2}} = 2145 * \frac{u^2}{2 * 9.81 \frac{m}{s^2}}$$

For equilibrium conditions:

$$h = h_f$$

with $h = 2m$ (maximum vertical difference in elevation between water levels in header tank, 481 m, and receiving tank, 479 m), total head available must equal sum of all head losses:

$$2m = 2145 * \frac{u^2}{2 * 9.81 \frac{m}{s^2}} = 109.3 \frac{s^2}{m} * u^2$$

$$\therefore u = \sqrt{\frac{2m}{109.3 \frac{s^2}{m}}} = 0.14 \frac{m}{s}$$

$$Q = u * A = u * \pi * \frac{d^2}{4} = 0.14 \frac{m}{s} * \pi * \frac{(0.1m)^2}{4} = 1.1 * 10^{-3} \frac{m^3}{s} = 1.1 \frac{l}{s}$$

Check for turbulence of flow with $\nu = 1.4 * 10^{-6} \frac{m^2}{s}$ for water at a temperature of 10ºC (Massey 1990: 20):

$\mathrm{Re} = u * \frac{d}{\nu} = 0.14 \frac{m}{s} * \frac{0.1m}{1.4 * 10^{-6} \frac{m^2}{s}} = 10000 > 2300$, therefore the flow is turbulent.

12.5 Smyrna

Steady State Operation

Flow Velocity and Volume Flow Rate

The section between header tank and receiving tank has a length of roughly 4,000 m:

$l = 4000m$

As the pipeline layout is largely conjectural, nothing is known about sudden bends, sharp entries or exits. Therefore only friction losses are considered. We can conservatively assume a pipe roughness $k = 4mm$, a value taken from modern engineering tables for an encrusted cast iron pipe (Gieck and Gieck 1990: Z9):

$\therefore$ for an average pipe diameter of 230 mm

$$\frac{k}{d} = \frac{4}{230} = 1.7 * 10^{-2}$$

$\therefore\ f = 0.045$ is independent of the Reynolds Number (Gieck and Gieck 1990: Z8)

Head loss due to pipe friction:

$$h_f = f * \frac{l}{d} * \frac{u^2}{2g} = 0.045 * \frac{4000}{0.23} * \frac{u^2}{2 * 9.81\frac{m}{s^2}} = 783 * \frac{u^2}{2 * 9.81\frac{m}{s^2}}$$

For equilibrium conditions:

$h = h_f$

with $h = 5m$ (maximum vertical difference in elevation between water levels in header tank, 188 m, and receiving tank, presumably at 183 m in the acropolis), total head available must equal sum of all head losses:

$$5m = 738 * \frac{u^2}{2 * 9.81 \frac{m}{s^2}} = 37.6 \frac{s^2}{m} * u^2$$

$$\therefore u = \sqrt{\frac{5m}{37.6 \frac{s^2}{m}}} = 0.36 \frac{m}{s}$$

$$Q = u * A = u * \pi * \frac{d^2}{4} = 0.36 \frac{m}{s} * \pi * \frac{(0.23m)^2}{4} = 15 * 10^{-3} \frac{m^3}{s} = 15 \frac{l}{s}$$

Check for turbulence of flow with $\nu = 1.4 * 10^{-6} \frac{m^2}{s}$ for water at a temperature of 10ºC (Massey 1990: 20):

$\mathrm{Re} = u * \frac{d}{\nu} = 0.36 \frac{m}{s} * \frac{0.23m}{1.4 * 10^{-6} \frac{m^2}{s}} = 59143 >> 2300$, therefore the flow is turbulent.

12.6 Segóbriga

Steady State Operation

Flow Velocity and Volume Flow Rate

The section between header tank and receiving tank has a length of roughly 2,500 m:

$$l = 2500m$$

As the pipeline layout is largely conjectural, nothing is known about sudden bends, sharp entries or exits. Therefore only friction losses are considered. We can conservatively assume a pipe roughness $k = 4mm$, a value taken from modern engineering tables for an encrusted cast iron pipe (Gieck and Gieck 1990: Z9):

$\therefore$ for a pipe diameter of 100 mm

$$\frac{k}{d} = \frac{4}{100} = 4*10^{-2}$$

$\therefore\ f = 0.065$ is independent of the Reynolds Number (Gieck and Gieck 1990: Z8)

Head loss due to pipe friction:

$$h_f = f*\frac{l}{d}*\frac{u^2}{2g} = 0.065*\frac{2500}{0.1}*\frac{u^2}{2*9.81\frac{m}{s^2}} = 1625*\frac{u^2}{2*9.81\frac{m}{s^2}}$$

For equilibrium conditions:

$$h = h_f$$

with $h = 40m$ (maximum vertical difference in elevation between water levels in header tank, 870 m, and receiving tank, 830 m), total head available must equal sum of all head losses:

$$40m = 1625*\frac{u^2}{2*9.81\frac{m}{s^2}} = 82.8\frac{s^2}{m}*u^2$$

$$\therefore u = \sqrt{\frac{40m}{82.8\frac{s^2}{m}}} = 0.7\frac{m}{s}$$

$$Q = u*A = u*\pi*\frac{d^2}{4} = 0.7\frac{m}{s}*\pi*\frac{(0.1m)^2}{4} = 5.5*10^{-3}\frac{m^3}{s} = 5.5\frac{l}{s}$$

Check for turbulence of flow with $\nu = 1.4 * 10^{-6} \frac{m^2}{s}$ for water at a temperature of 10ºC (Massey 1990: 20):

$\mathrm{Re} = u * \frac{d}{\nu} = 0.7 \frac{m}{s} * \frac{0.1m}{1.4 * 10^{-6} \frac{m^2}{s}} = 50000 > 2300$, therefore the flow is fully turbulent.

	pipe length	pipe diam.	Max. drop	avail. Head	flow rate	flow velocity	max. press.
Aspendos	1,718 m	0.28 m	46 m	15 m	65 liters/s (Kessener 2000a: 118, "65 liters/s")	*ca.* 1.06 m/s	4.5 bar
Yzeron	5,800 m	0.18 m (6-7 pipes?)	98 m	40 m	18 liters/s per pipe (Burdy 2002a: 173, "13-15 liters/s per pipe")	*ca.* 0.71 m/s	9.6 bar
Pergamum	3,470 m	0.22 m?	198 m	41 m	40 liters/s (Garbrecht 1978: 7, "45 liters/s"; 1987a: 27, "30 liters/s")	*ca.* 1.05 m/s	19.4 bar
Alatri	3,300 m	0.1-0.15 m	101 m	17 m (2 m?)	3.1 liters/s (1.1 liters/s?)	*ca.* 0.4 m/s	9.9 bar
Smyrna	4,000 m	0.23 m	158 m	5 m	15 liters/s	*ca.* 0.36 m/s	15.5 bar
Segóbriga	2,500 m	0.1 m	70 m	40 m	5.5 liters/s	*ca.* 0.7 m/s	6.9 bar

Table 12-1: Summary of Main Flow Properties

The values for the flow rate represent the maximum possible flow of the inverted siphon, determined solely by the geometry of the pipeline. In reality the flow rate would have depended naturally on the annually varying yield of the sources that fed the aqueducts. If a source yielded less water than the numbers given above, then, of course, the inverted siphon also transported less water. If the source yielded more water, the amount superior to the numbers given above overflowed at the header tank and may have been put to different use. The above calculations reproduce well the results for maximum flow rate for Aspendos, Yzeron, and Pergamum. Slight differences in the results for Yzeron and Pergamum are due to the assumption of different wall roughness and hence different friction factors (*f*=0.025 by Garbrecht for Pergamum; unknown by Burdy for

Yzeron). Flow rates for Alatri, Smyrna, and Segóbriga, determined by the same method as for Aspendos, Yzeron, and Pergamum, are relatively small (1.1 liters per second for Alatri, 15 liters per second for Smyrna, and 5.5 liters per second for Segóbriga). The flow rate for Alatri is very small (1.1 liters per second) due to the small difference in elevation between header tank and receiving tank (2 m). The expense of building an inverted siphon of lead pipes for a distance of 3.3 km seems disproportionate for such a small flow rate. It is tempting to assume that the flow rate must have been bigger to make the project worthwhile. Therefore the conjectured geometry on which the calculation is based may be faulty. The flow rate could have been bigger if the inverted siphon consisted of more than just one pipe. But the relative expense in material would have been the same, as each pipe still would have been capable of transporting only 1.1 liters per second. Perhaps the inverted siphon had a total available head of more than just 2 m. The position of the receiving tank is clearly indicated by the inscription of Betilienus. Therefore a source of error may be the position of the header tank, based on Bassel's observations from 1881. Lewis' reconstruction of the inverted siphon shows the header tank at 490 m, and the receiving tank at 473 m, *i.e.* with a total head of 17 m. Using Lewis' geometry, the flow rate changes to 3.1 liters per second—still a relatively small amount that does not appear to stand in a reasonable relation to the expense of building, operating, and maintaining the system.

The volume flow rate at Smyrna (15 liters per second) is in the range of value for a single pipe at Yzeron (18 liters per second). At Smyrna, the geometry of the inverted siphon—in particular the position of the header tank—is uncertain. A total head of only 5 m is relatively small, compared with the other big inverted siphons in question (between 15 m at Aspendos and 41 m at Pergamum). Compared with the likely contemporary system at Pergamum, of similar pipe diameter (0.22 m at Pergamum *vs.* 0.23 m) and length (3,470 m at Pergamum *vs.* 4,000 m), one would expect a similar positioning of header tank vis-à-vis the receiving tank (a vertical distance of 41 m at Pergamum). Therefore perhaps the position of the header tank at Smyrna must be reconsidered. In order to get a similar flow rate at Smyrna as at Pergamum (*ca.* 40 liters per second), the header tank would have to be located *ca.* 35 m above the receiving tank and 33 m above the location assumed by Weber for the header tank, at an elevation of 218 m. The hill where the inverted siphon likely had its beginning reaches such an elevation *ca.* 750 m east of Weber's location of the header tank.

The *qanat* that fed the aqueduct at Segóbriga yielded in summer of 2006 a flow rate of approximately 0.5 liters per second. Assuming a similar yield in antiquity and considering that the Fuente de la Mar was supplemented to an unknown extent by the Fuente de las Zarzas, a maximum flow rate of 5.5 liters per second during the winter months, when precipitation is high (47 mm in December *vs.* 9.4 mm in July at Madrid), seems reasonable for Segóbriga, especially considering the relatively narrow pipe diameter (0.1 m).

The numbers for the maximum pressures represent the values that could be measured if the water in the pipeline were at rest and the inverted siphon were filled to the top of the header tank—a situation that could have occurred only if the pipeline were full and the outflow were closed off by some valve. In operation, the pressure would decrease along the length of the pipe according to the hydraulic gradient. The true maximum static pressure at the lowest point in the pipe would then depend on the position of the lowest point relative to the header tank and would be the lower the further from the header tank that point is located.

For the next step it is necessary to determine if and how big an air bubble would have accumulated down slope of the intermediate high points, how these potential air bubbles were purged, and if they could have caused water hammer.

13. Air Bubbles

High points in inverted siphons are the cause of air blocks that may render the pipeline useless. For the labeling refer to the schematic in the Appendix: Figure 0.41. During the filling process of an empty pipeline water will first collect at point A. It will then rise up evenly on both sides until it overflows at point B and runs down to point C. As the water rises on both sides of point C, the air in section BC is trapped, since it cannot escape either upstream or downstream. As the water continues to rise at point C, the trapped air bubble is compressed. The top of this compressed air bubble will always be at point B, and the bottom will be pushed higher and higher towards point B as the pressure continues to build up. When the water level is high enough, it will overflow at point D down to point E, creating a second trapped air pocket in section DE. From point E the water level will rise towards the receiving tank as long as there is sufficient pressure from the source to push it higher. The final equilibrium will be reached as shown in Appendix: Figure 0.42 (Jordan 1984: 194-5). In a gravity-fed pipeline, one determining factor for the volume flow rate is the total available head, *i.e.* the vertical distance between the elevation of header and receiving tank. If the vertical height of the air bubble is higher than the available head, the inverted siphon will not work. It is necessary to provide a means to vent the air bubble, be it in the form of a tower (Yzeron) or in the form of holes in the pipe wall. Since this problem occurs only during filling, the holes can be closed off in normal operation and be reopened again when the inverted siphon must be refilled again, *e.g.* after maintenance works. In the same way, a feature is necessary that allows air to flow into the pipeline and fill the space vacated by the water when it is drained from the inverted siphon.

Jordan (1984: 194-202) offers a procedure to calculate the size of the air block, which allows us to investigate if high points occurring in a pipeline will pose a problem to the function of the system. The procedure is easily applicable to the ancient inverted siphons. The method assumes that a small flow will always make it past the air blocks. As the air bubble is compressed, some of the air will dissolve and be absorbed by the water. This absorption causes the air block to shrink and the bottom of the air bubble, B', to rise gradually. Jordan (1984: 197) states that all trapped air will eventually be removed by the water within a day. The assumption is that initially a minimum flow rate of 10 % of the design flow rate of the inverted siphon, *i.e.* the ideal flow rate determined solely by the system geometry, will make it past the air block.

In the first step the total static pressure in the air bubble is determined from the "compression head H_c" (*cf.* Appendix: Figure 0.42), *i.e.* the vertical distance between header tank and the top of the first air block. The relevant equation is: $p = \rho * g * H_c + p_0$, or simplified $p = (0.1 * H_c) + 1$ (Jordan 1984: 197). The resulting pressure is given in bar.

Aqueduct	**compression head H_c [m]**	**total static pressure of first air bubble [bar]**
Pergamum	134	14.4
Yzeron	7	1.7
Smyrna	27	3.7
Alatri	35 (Lewis 1999)	4.5
Segóbriga	30	4.0

Table 13-1: Static Pressure of First Air Bubble

The volume of the uncompressed air bubble is determined by the length of the pipeline section BC (Appendix: Fig. 0.41) multiplied with the cross-sectional area of the pipe. Boyle's Law is used to determine the volume of the compressed air bubble (Jordan 1984: 197). Dividing the compressed volume by the cross-sectional area of the pipe again gives the length of the compressed air bubble in the pipe represented by section BB' in Appendix: Figure 0.42. Due to the poor state of preservation of all aqueducts, the length of section BC is only approximate. The procedure is demonstrated below for the pipeline at Pergamum. The results are summarized for all pipelines in table 13-1.

$$V_{uncompressed\ ,Pergamon} = 750m * 0.038m^2 = 28.5m^3$$

$$V_{compressed\ ,Pergamon} = \frac{V_{uncompressed\ ,Pergamon}}{p_{air}\,/p_{atm}}$$

where air pressure p_{air} is equal to the static pressure of the first air bubble.

$$V_{compressed\ ,Pergamon} = \frac{28.5m^3}{14.4\ bar/1.01bar} = 2m^3$$

$$l_{compressed\ ,Pergamon} = \frac{V_{compressed\ ,Pergamon}}{cross - sectional\ area\ of\ pipe} = \frac{2m^3}{0.038m^2} = 53m$$

aqueduct	**length of section BC [*ca.* m]**	**cross-sectional area of pipe [m^2]**	**volume of uncompressed bubble [*ca.* m^3]**	**volume of compressed bubble [*ca.* m^3]**	**length of compressed bubble [*ca.* m]**
Pergamum	750	0.038	29	2.0	53
Yzeron	2,100	0.025	53	31	1,240
Smyrna	650	0.042	27	7.3	174
Alatri	350	0.008	2.8	0.6	75
Segóbriga	600	0.008	4.8	1.2	150

Table 13-2: Calculation of Compressed Bubble Size

The next step is the calculation of the head loss that results from the trapped air bubble. This value is determined by the vertical distance between the top and the bottom line of the compressed bubble, which is found by multiplying the length of the compressed bubble with the sine of the slope angle. The slope angle, too, is only conjectural, due to the poor state of preservation of the pipelines and due to possible, though unlikely, changes in the topography over the millennia.

Aqueduct	**slope angle [*ca.* º]**	**head loss from first air block [*ca.* m]**
Pergamum	5	4.6
Yzeron	3	65
Smyrna	6	19
Alatri	6	7.8
Segóbriga	2	5.2

Table 13-3: Head Loss from First Air Block

The equivalent head, H_e, of this air block is found by the equation: $H_e = 10 * (p - 1.0)$, where p is the pressure of the air block. This value added to the elevation of the low end of the compressed air block gives the highest elevation that the assumed minimum flow rate of 10 % of the design flow rate will reach (Jordan 1984: 198). This elevation is not a.s.l., but relative to the absolute low point of the respective pipeline.

Aqueduct	**p in [bar]**	**H_e in [m]**	**maximum possible elevation in [*ca.* m]**
Pergamum	14.4	134	194
Yzeron	1.7	7	32
Smyrna	3.7	27	148
Alatri	4.5	35	92
Segóbriga	4.0	30	45

Table 13-4: Maximum Possible Elevation

According to this calculation, at Pergamum, Smyrna, Alatri, and Segóbriga the water would eventually reach the elevation of the header tank despite the air block. At Yzeron, the air block would prevent the inverted siphon from starting up. The tower, therefore, was necessary to vent the air bubble to render the pipeline functional.

Of these aqueducts, however, those at Pergamum, Smyrna, and Alatri, have a second high point where a second air block would form. The same procedure applies to the calculation of the second air block. The pressure of the second bubble is found by the equation: $P_d = P_b + 0.1 * (H_b - H_d)$ (Jordan 1984: 198). For labeling *cf.* Appendix: Figure 0.43. The remaining procedure is the same as above.

Aqueduct	**hydrostatic head H_b [m]**	**hydrostatic head H_d [m]**	**total static pressure of second air bubble [bar]**
Pergamum	60 – 4.6 = 55.4	70	13
Smyrna	70 – 19 = 51	30	5.8
Alatri	35 – 7.8 = 27.2	50	2.2

Table 13-5: Total Static Pressure of Second Air Bubble

aqueduct	**length of section DE [*ca.* m]**	**cross-sectional area of pipe [m^2]**	**volume of second uncompressed bubble [*ca.* m^3]**	**volume of second compressed bubble [*ca.* m^3]**	**length of second compressed bubble [*ca.* m]**
Pergamum	450	0.038	17	1.3	34
Smyrna	400	0.042	17	2.9	69
Alatri	450	0.008	3.6	1.6	200

Table 13-6: Length of Second Compressed Air Bubble

aqueduct	**slope angle [*ca.* °]**	**head loss from second air block [*ca.* m]**
Pergamum	5	3.0
Smyrna	11	13
Alatri	4	14

Table 13-7: Head Loss from Second Air Block

aqueduct	**p in [bar]**	**H_e in [m]**	**maximum possible elevation in [*ca.* m]**
Pergamum	13	120	187
Smyrna	5.8	48	125
Alatri	2.2	12	78

Table 13-8: Maximum Possible Elevation

All these numerical results are based on conjecture. They necessarily contain rounding errors and do not take friction into account. Therefore, they must be considered rather optimistic. They nonetheless give an indication of possible problems posed by air blocks at the intermediate high points. The relative elevation of the receiving tank above the low point of the inverted siphon at Pergamum is roughly 160 m. The flow rate of the water, therefore, would have been sufficient to transport both air blocks out of the way and reach the header tank, as the maximum elevation that the flow would have reached according to the method proposed by Jordan is 187 m. At Smyrna, the relative elevation of the receiving tank above the absolute low point was 125 m. The volume flow rate would have been at the limit of the ability to purge the air block and establish nominal flow with a maximum theoretical elevation of also 125 m. The theoretical result neglects friction and is, therefore, optimistic. The inverted siphon at Smyrna would probably have required some feature that allowed the bleeding of the air blocks. At Alatri, the relative elevation of the receiving tank above the low point was roughly 83 m, according to Lewis' (1999) reconstruction. The volume flow rate would likewise have been at the limit of the ability to purge the air block and establish nominal flow with a maximum theoretical elevation of 78 m. The theoretical result neglects friction and is, therefore, optimistic. The inverted siphon at Alatri, like that at Smyrna, would probably have required some feature that allowed the venting of the air blocks.

Since the vertical distance between the high points and hydraulic gradient at both Smyrna and at Alatri would have been too large for towers of the type at Yzeron, it is conceivable that these inverted siphons were fitted with pipes containing holes in the side walls for the purging of the air blocks. These holes, if they existed, may have been closed with tightly secured bungs as soon as the water was visible through them, indicating that nominal flow conditions were nearly established. For an inverted siphon with more than one high point, all holes would have been open during the filling process and closed when water became visible. In practice this means that the air bubble from the first high point would have been purged first, as it would have been the first to form as water filled the first portion of the inverted siphon before trickling across the high point into the following portion.

14. Water Hammer

When a column of cars is driving towards a set of traffic lights and the lights turn red, the first car in the column will stop. The second car will pull up to the bumper of the first car and stop slightly later. The third car will pull up to the bumper of the second car and stop slightly later again, *etc*. The halted cars will be closer together than those that are still moving, *i.e.* the density of cars is increasing. Thus an observer from above will be able to see a backwards moving “wave” of cars coming to a consecutive halt. Something similar happens to water “particles” in a column of water flowing in a pipe when that column suddenly decelerates, for example, because of a fast closing valve/tap. Since water is essentially incompressible, a pressure wave will form and move upstream from the valve/tap. This phenomenon is known as water hammer. It is possible to calculate the increase in pressure across that wave and to determine whether the increase will cause damage to the water pipe. Kessener repeatedly states (2000a, 2001, 2002a, 2002b, 2003) that alleviation of the effects of water hammer was the purpose of the towers at Aspendos. But as he (2000a: 126) quite rightly states, there is no evidence for the presence of taps or stop cocks to indicate that the flow in the long-distance pipelines was ever shut off. The situation is different for urban distribution networks, where taps occur in the archaeological record (Jansen 2001, 2005). The water gushing from a ruptured pipe, used by Ovid (*Met.* 4.121-4) as a simile for blood gushing from a wound, could have its background in daily experience with pipes damaged by water hammer that occurred after the sudden closure of a water tap. The secondary distribution towers, *e.g.* in Pompeii (Larsen 1982), would have been efficient devices against water hammer, as they kept the uninterrupted lengths of pipe relatively short, so that pressure waves were always limited to short sections of pipeline.

Water hammer was not a problem in ancient inverted siphons because, in contrast to urban pipelines, water flowed through them continuously. If water hammer had been a frequent problem, many more inverted siphons would have been equipped with structures like the towers at Aspendos. Since these towers are unique, and there are much longer and deeper inverted siphons than that at Aspendos without any such provisions, it is safe to assume that water hammer did not occur. Kessener's (2000a:126-9; 2002b: 189, n. 23) assertion that water hammer is caused by escaping air pockets is based on an erroneous interpretation of Vitruvius' term *vis spiritus* (Vitr. 8.6.6). As I have shown in Chapters 2.1 and 3, Vitruvius is not concerned with air. Kessener states that water hammer occurred for two reasons: first, as the flowing water moves underneath an air bubble that has collected at a high point it will draw some of the air from the bubble with it. According to Kessener (2000a: 127), referring to Schnappauf (1966), this change in the volume of the air bubble can cause a sudden change in the flow velocity of the water column, which results in water hammer. Schnappauf (1966: 373), however, specifically states that there is relatively little danger of water hammer occurring if the static pressure is *ca.* 5 atü (4.9 bar) or higher, which was approximately the case at Aspendos on the level of the main bridge (4.5 bar). Kottmann and Schmitt (1980: 61; Kottmann 1984b) add that the danger is present mainly for flow velocities between 0.2-0.3 m/s. These values are results from experiments conducted by Gandenberger (1957: 66). The precise mechanism of the occurrence of water hammer under these conditions is unknown to Kottmann and Schmitt. Hence, the danger may have been relatively high at Alatri

(0.4 m/s) and Smyrna (0.35 m/s), although we remain somewhat uncertain about the layout of these two aqueducts. The other aqueducts under consideration in this study had flow velocities of *ca.* 0.7 m/s (Segóbriga, Yzeron) and *ca.* 1.05 m/s (Pergamum, Aspendos). The static pressure in the pipeline at Aspendos would have been reduced locally by the towers, which thus would have created the problem in the first place, through pressure reduction on the one hand, and through creating an air block on the other. It makes no sense to build the towers as a solution to a problem that without the towers would not have even occurred.

According to Kessener (2000a: 127), a similar, but worse problem is caused by leaks in the pipe wall. Air bubbles, transported downstream by the flowing water, may get stuck at uneven points in the inside wall surface of the pipeline. If there happens to be a leak in the pipe wall in such a spot, the air bubble will escape rapidly. As water occupies the space vacated by the air bubble, the water column upstream from such a point will be accelerated. As soon as the air bubble has completely disappeared, the water column will be decelerated again and water hammer is the result, causing potentially a pressure increase of 100% at Aspendos. The release of the air bubble, according to Kessener, is accompanied by hissing and sputtering. As an analogy, Kessener (2000a: 127, n. 68) mentions the sputtering from a garden hose or a freshly repaired household tap. This analogy, however, is flawed, as an air bubble in a garden hose escapes through the nozzle in line with the main flow direction of the water. At the local constriction, represented by the nozzle, the air bubble is located between two separate columns of water, one in front of and one behind the bubble. As the air bubble escapes through the nozzle, it flows much faster than the preceding or succeeding water. Hence the water behind the bubble is, indeed, accelerated and then suddenly decelerated, as the following water column hits the nozzle. In contrast, an air bubble escaping through a leak in the side wall of a pipe flows at right angles to the main flow direction. The air bubble causes a local constriction that gradually expands as the air bubble escapes. The water column upstream of the bubble does not suddenly accelerate and then decelerate because in the axial direction of the pipe the water column is never interrupted, and the flow velocity of the water never changes upstream or downstream from the local constriction. There is no occurrence of two water columns flowing at different velocities and colliding, and hence no water hammer will occur. Due to his erroneous assumption, Kessener uses a method that, in my opinion, is not applicable to the special case of a laterally escaping air bubble to calculate the magnitude of the pressure increase in water hammer (Falvey 1980: 71).

Even if water hammer occurred at Aspendos and caused a pressure increase of 100%, the limestone pipeline would have been capable of withstanding that pressure. A pipe under high internal pressure is in danger of bursting longitudinally rather than around its circumference. An internal pressure of 90 bar (2*45 bar maximum pressure due to 100% increase) in the pipe from Aspendos, with an internal diameter of 0.28 m, leads to a tensile stress of 1,145.5 kN/m^2 in the thinnest section (11 cm wall thickness) of the pipe wall. The rupture modulus of limestone is in the range of 500-2,000 lb/in^2 or 3,447-13,790 kN/m^2 (Avallone and Baumeister 1996: 6-144), 3-12 times higher than the tensile stress occurring according to Kessener’s pressure increase. Water hammer would not have damaged the pipeline.

15. Computational Fluid Dynamics

The decade-long discussion about the purpose of "hydraulic towers" and the exact meaning of *colluviaria* reveal a significant gap in our knowledge of the system behavior of long-distance pipelines. The interaction of water and residual air in a gravity-flow pipeline with intermediate high points is a complicated phenomenon that is not immediately accessible to intuition. While scholars have repeatedly established the link between hydraulic towers and air in the pipeline and have made the connection with *colluviaria*, the precise mechanics of the incidence of air in the line has generally been unclear. The lack of scale-experiments, such as those conducted by Hodge (1984), Chanson (2000), or Oleson (Dalley and Oleson 2003) in other contexts, represented a gap that was closed by Nikolic (2003). Problems of similitude render such experiments useful only in qualitative, but not in quantitative terms. The study of complex fluid dynamics problems involving models poses a challenge because the model is usually smaller than the original. While the scale of the pipe geometry can be easily modified, the scale of the physical properties of water and air are fixed. It is insufficient for the generation of meaningful results to reduce only the geometry of the pipeline to a certain scale without adjusting also the flow properties, such as the time rate of the fluid motion and associated forces acting on the fluid and on the pipe boundaries. In fluid dynamics terminology, scaling of the system requires that geometric, kinematic, and dynamic similarity are maintained (Massey 1990). A reconstruction of a sample pipeline in a scale of 1:1 can produce results that are directly applicable to the original aqueduct. It is evident that such a project is not likely to materialize for financial reasons and because of the space requirements of a 1:1 scale model. Alternatively, it is possible to reproduce the flow conditions in a scale-model by adjusting the flow in the model to the same Reynolds Number as the original. The Reynolds Number for pipe flow is:

$$\mathrm{Re} = \frac{u * d}{\nu}$$

where u: mean flow velocity

d: pipe diameter

ν: kinematic viscosity of the fluid

The Reynolds Number in pipe flow depends on flow velocity, the fluid's viscosity, and the characteristic length, which, in the case of pipe flow, is the pipe diameter. The flow in a scaled-down pipeline model that has the same pipe diameter as the original line will, therefore, be geometrically similar to the flow in the original system. Nonetheless, critical flow properties, such as maximum flow velocities and pressures, will not be the same in the scaled-down model as in the original. Computer simulation offers an alternative method for the reproduction of water flow in a pipeline. Computer simulation is inexpensive and very flexible. Pipe geometries can be modified easily and frequently, according to the need of the research question.

Commercially available CFD-software packages are designed for industrial applications and for specific tasks. It is necessary to choose the appropriate software for the problem at hand. Two software packages are in wide use: Flow-3D© by Flow Science Inc., based in Santa Fé, New Mexico, and Fluent© by Fluent Inc., based in Lebanon, New Hampshire. Flow-3D© is specifically designed for the simulation of free-surface flow problems, such as open channel flow. Ortloff utilized Flow-3D© to investigate the water supply systems of Priene (Ortloff 1998), Ephesus (Ortloff and Crouch 2001), and Petra (Ortloff 2005). Fluent© is a widely used CFD-package, very versatile, and capable of handling the same types of problem as Flow-3D©. Due to its versatility and availability at the University of Victoria, Fluent© was the software of choice for the investigation of the long-distance pipelines. Nobody had used this software for this particular sort of simulation before.

The CFD-work was made possible by the generosity of Professor Ned Djilali from the Department of Mechanical Engineering and through the help and expertise of his associates, Dr. Gonçalo Pedro and Dr. Jay Sui. The simulations were executed using the following equipment: Microway Quadputer-Navion 4U Quad SMP Server with a clock speed of 3.0 GHz and 128 GB of memory. The computation ran on 12 processors in parallel on the operating system Novell Suse Linux 10.1.

The model and the computational mesh were generated with Gambit 2.2 (2003) by Fluent Inc. The computations were performed with Fluent© 6.1 (*Fluent* 2003). Remote login to the system in the Department of Mechanical Engineering was done through PuTTY (Tatham 2005), a free Telnet and SSH client for Windows. Interaction with the remote desktop of the system in Mechanical Engineering was enabled through VNC Viewer (*VNC Viewer Free Edition* 2005).

The problem of any simulation is to ensure that the model accurately reproduces the behaviour of the original. The results from a computer simulation are only as good as the model and the boundary conditions defined by the operator. For a computational domain as large as a portion of an ancient aqueduct (*e.g.* the siphon at Aspendos, *ca.* 1.7 km long), the choice of model requires to find a balance between accuracy and computational economy. The simulation of the complete filling process of such an aqueduct takes a very long time. Assuming the velocity of inflow from the aqueduct channel is 1.5 m/s through a cross-sectional area roughly equivalent to that of the pipeline (*ca.* 0.06 m²), the roughly 1.7 km long pipeline will take 1,133 seconds (or 18 minutes and 53 seconds) in real time to fill. If the CFD-software solves the model equations in time steps of one thousandth of a second, and each time step takes *ca.* 30 seconds to compute, the computation of the complete filling cycle will take 393 days to complete. A simulation of a model of the pipeline at Aspendos with the length (but not the pipe diameter) reduced to a scale of 1:10 will take roughly 39 days to complete.

Since the computer simulation of ancient aqueducts is, with some notable exceptions (Ortloff 1998; Ortloff and Crouch 2001; Ortloff and Kassinos 2003), a novel approach, the establishment of a valid methodology was a prime target of this experiment. Conservative simulations started with a 2D-computer model of a simple vessel filling with water. These preliminary tests were necessary to establish that the software is capable of tracking the rising interface between water and air in the filling process of a vessel with a simple geometry. In order to eliminate as much computational load as possible, the model was built in only two dimensions. Once the initial experiment with the basic vessel shapes was successful, the next step was to modify the geometry from a simple “bowl” shape to a geometry approximating the shape of a rubber hose used in a physical experiment to simulate a small-scale inverted siphon with intermediate high point (Nikolic 2003). Figure 15.1 shows the geometry of the model. Water enters the funnel at the top (height 0.3 m, width at top 0.5 m, width at bottom 0.1 m) through a section 0.02 m wide. The hose diameter is 0.1 m. The straight vertical sections of the hose are 0.5 m long, and the diameter of the bends is 1 m. The length of the virtual hose was, therefore, 5.7 m. The computational grid consisted of 34,578 mesh points.

The simulation of this experiment was successful. The computer-generated water behaved in exactly the same manner as the real water behaved in the scale experiment. Water entered the hose on the right edge of the funnel at a rate of 0.5 m/s. The mpeg-movie shows clearly the air bubble forming downstream from the intermediate high-point, as the water level rises in the second branch of the W-shaped hose.

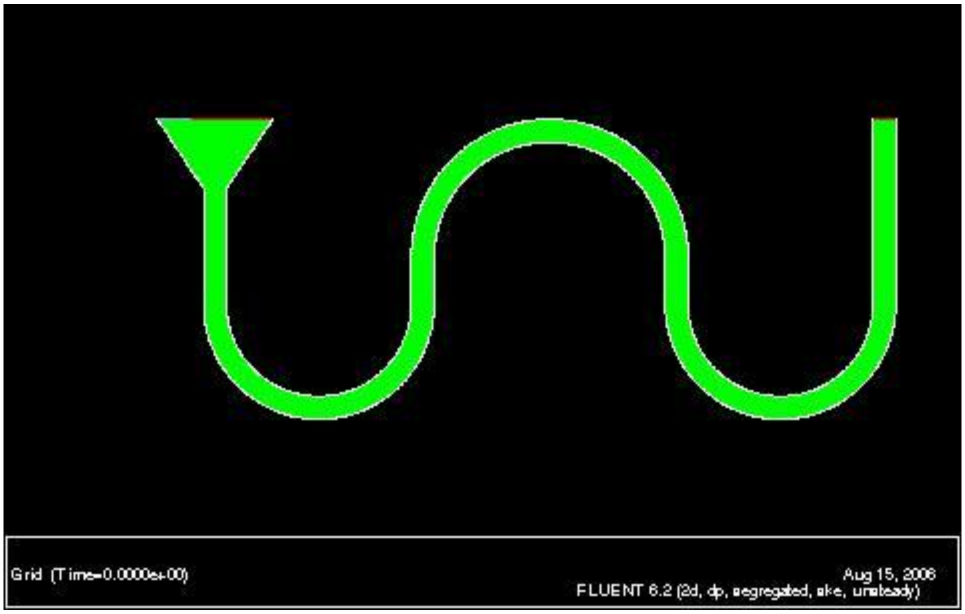

Figure 15.1: Geometry

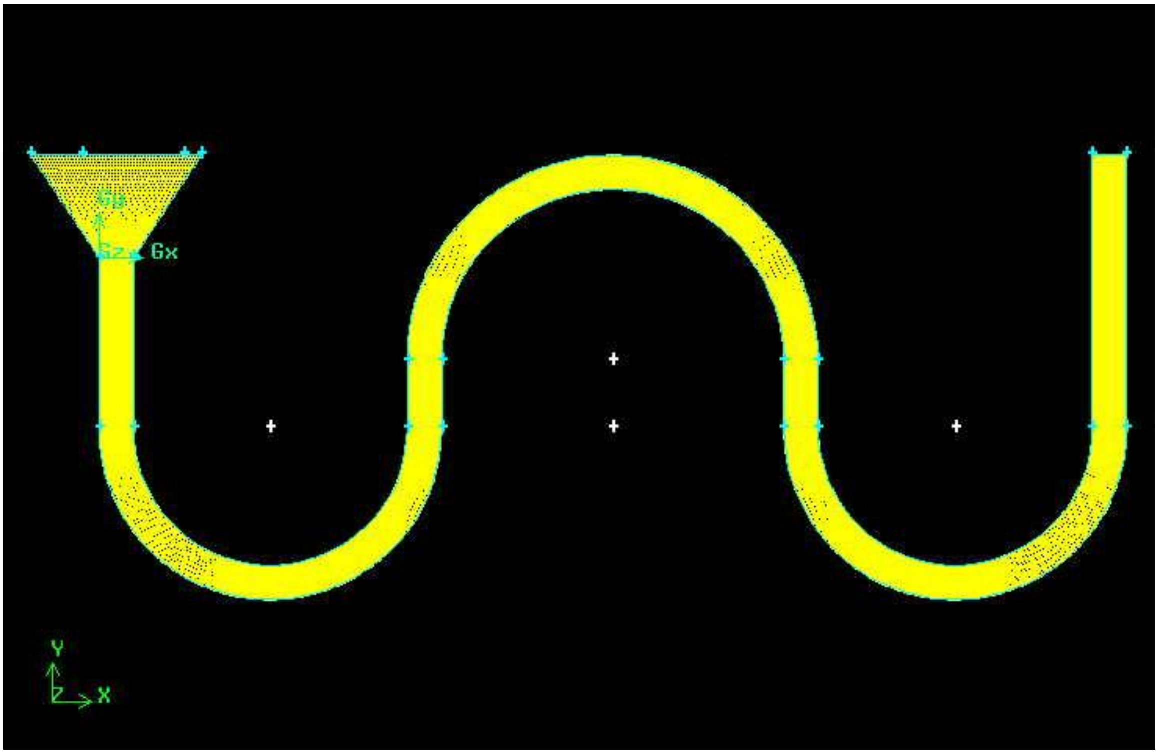

Figure 15.2: Computational Mesh

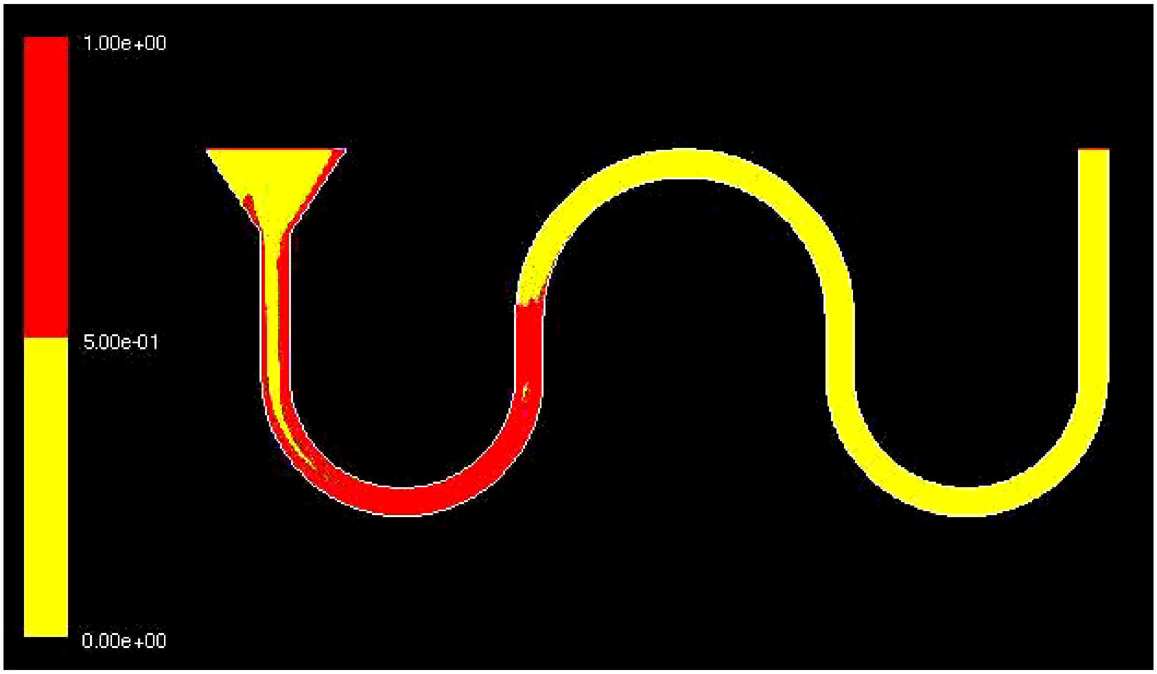

Figure 15.3: Flow at 11 s

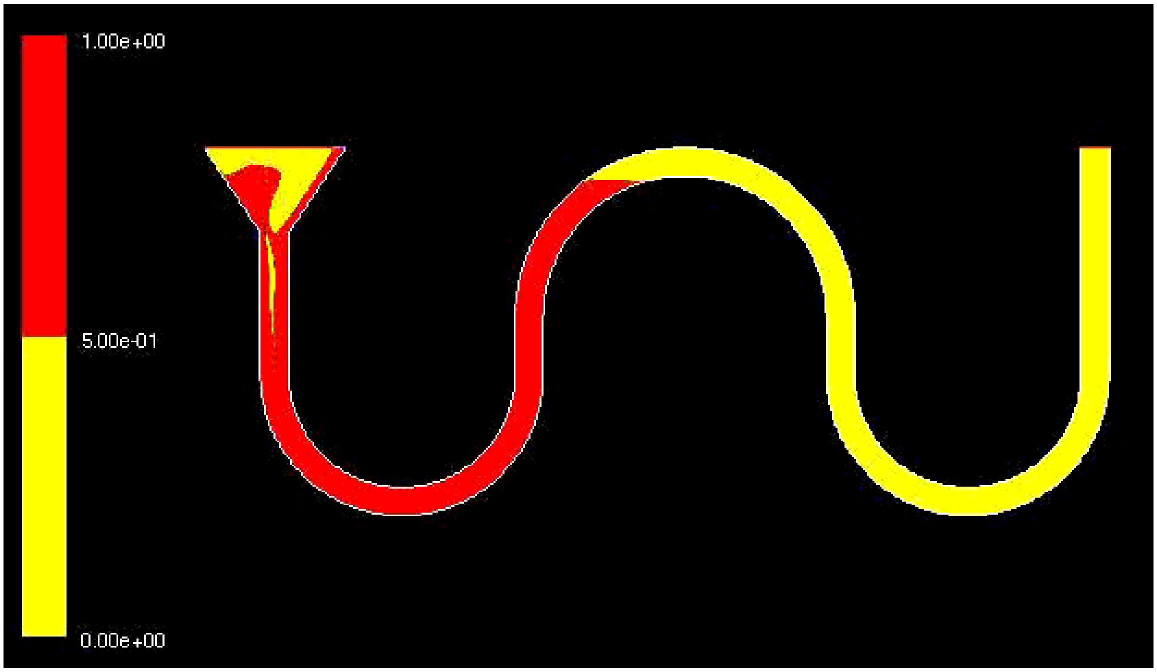

Figure 15.4: Flow at 20 s

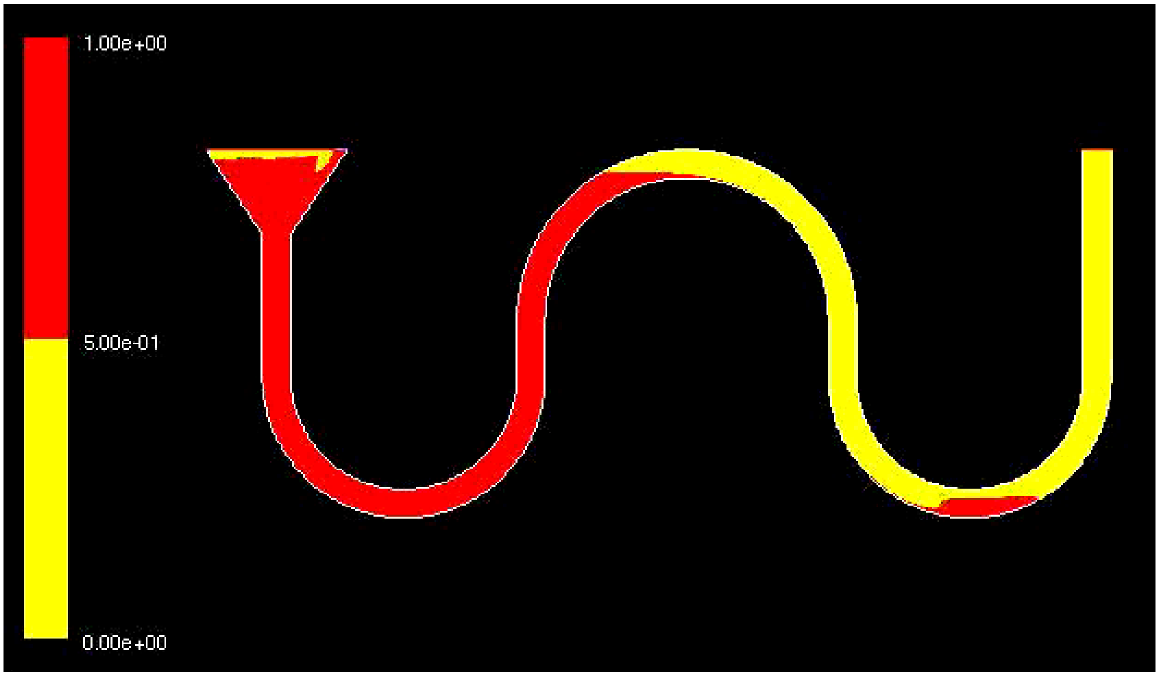

Figure 15.5: Flow at 32 s

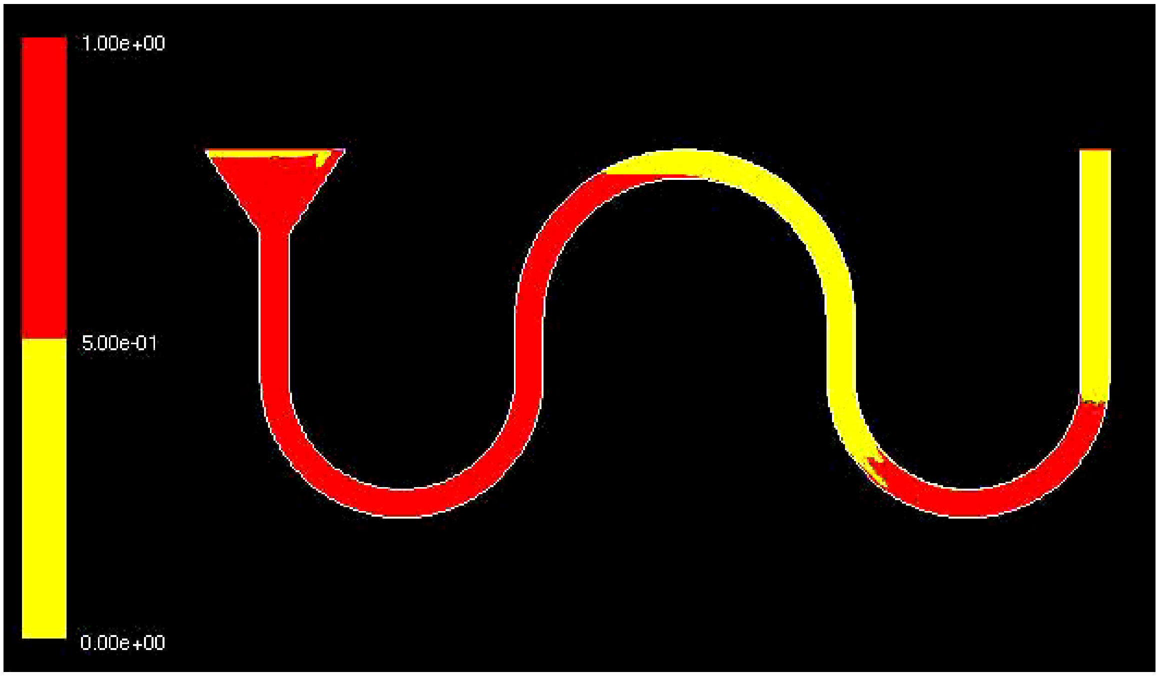

Figure 15.6: Flow at 52 s

The model geometry and the computational mesh were generated with Gambit 2.2. The procedure for creating the 2D-geometry is straightforward. Using an arbitrary, usually Cartesian, coordinate system, the geometry is created from individual entities of different order topology, moving from lower to higher order: vertices, edges, faces, volumes (3D only). This approach is known as “bottom-up”. The vertices are located at significant points of the geometry, which are connected by straight or curved edges. The edges are connected to create a 2D-face. The face is then covered with the computational mesh. The meshing procedure, too, moves from entities of lower to those of higher topology. The edges are meshed first, by defining a node density, *i.e.* the distance between consecutive points. Then, the 2D-face is meshed on the basis of the node density along the edges. Finally, it is necessary to define the boundary types, *i.e.* the edges of the inlet and outlet of the pipe. The default boundary type is “wall”, therefore, the wall boundary need not be specifically defined. The following is a transcript of the journal-file that Gambit records during the creation of a model. The origin of the coordinate system (0/0/0) is located on the left lower edge of the funnel. All coordinates are in centimeters.

```
/ Journal File for GAMBIT 2.2.30, Database 2.2.14, lnx86 BH04110220
/ Identifier “rohr-diss-2d”
identifier name “rohr-diss-2d” new nosaveprevious
vertex create coordinates 0 0 0
vertex create coordinates 10 0 0
vertex create coordinates 10 -50 0
vertex create coordinates 0 -50 0
vertex create coordinates 50 -50 0
vertex create coordinates 90 -50 0
vertex create coordinates 100 -50 0
vertex create coordinates 150 -50 0
vertex create coordinates 200 -50 0
vertex create coordinates 210 -50 0
vertex create coordinates 250 -50 0
vertex create coordinates 290 -50 0
vertex create coordinates 300 -50 0
vertex create coordinates 300 0 0
vertex create coordinates 290 0 0
vertex create coordinates 50 -100 0
vertex create coordinates 50 -90 0
vertex create coordinates 250 -90 0
vertex create coordinates 250 -100 0
vertex create coordinates 150 0 0
vertex create coordinates 150 10 0
edge create center2points “vertex.5” “vertex.3” “vertex.17” minarc arc
edge create center2points “vertex.5” “vertex.17” “vertex.6” minarc arc
edge create center2points “vertex.5” “vertex.4” “vertex.16” minarc arc
edge create center2points “vertex.5” “vertex.16” “vertex.7” minarc arc
edge create center2points “vertex.8” “vertex.6” “vertex.21” minarc arc
edge create center2points “vertex.8” “vertex.21” “vertex.10” minarc arc
edge create center2points “vertex.8” “vertex.7” “vertex.20” minarc arc
edge create center2points “vertex.8” “vertex.20” “vertex.9” minarc arc
edge create center2points “vertex.11” “vertex.10” “vertex.18” minarc
arc
edge create center2points “vertex.11” “vertex.9” “vertex.19” minarc arc
edge create center2points “vertex.11” “vertex.18” “vertex.12” minarc
arc
edge create center2points “vertex.11” “vertex.19” “vertex.13” minarc
arc
vertex create coordinates 30 30 0
vertex create coordinates -20 30 0
edge create straight “vertex.12” “vertex.15” “vertex.14” “vertex.13”
```

```
edge create straight “vertex.4” “vertex.1” “vertex.23” “vertex.22”
“vertex.2” \
  “vertex.3”
undo begingroup
edge mesh “edge.16” “edge.20” successive ratio1 1 intervals 20
undo endgroup
undo begingroup
edge mesh “edge.3” “edge.1” successive ratio1 1 intervals 25
undo endgroup
undo begingroup
edge mesh “edge.4” “edge.2” successive ratio1 1 intervals 25
undo endgroup
undo begingroup
edge mesh “edge.7” “edge.5” successive ratio1 1 intervals 25
undo endgroup
undo begingroup
edge mesh “edge.8” “edge.6” successive ratio1 1 intervals 25
undo endgroup
undo begingroup
edge mesh “edge.10” “edge.9” successive ratio1 1 intervals 25
undo endgroup
undo begingroup
edge mesh “edge.12” “edge.11” successive ratio1 1 intervals 25
undo endgroup
undo begingroup
edge mesh “edge.13” “edge.15” successive ratio1 1 intervals 20
undo endgroup
undo begingroup
edge mesh “edge.17” “edge.19” successive ratio1 1 intervals 20
undo endgroup
undo begingroup
edge mesh “edge.14” “edge.18” biexponent ratio1 1.005 intervals 40
undo endgroup
face create wireframe “edge.1” “edge.2” “edge.3” “edge.4” “edge.5”
“edge.6” \
  “edge.7” “edge.8” “edge.9” “edge.10” “edge.11” “edge.12” “edge.13” \
  “edge.14” “edge.15” “edge.16” “edge.17” “edge.18” “edge.19” “edge.20”
real
face mesh “face.1” map size 1
face mesh “face.1” map size 4.1439097
face mesh “face.1” map size 3.8849153
save
edge split “edge.18” meshnode 75
physics create “WATER_INLET” btype “VELOCITY_INLET” edge “v_edge.21”
physics create “OUTLET” btype “PRESSURE_OUTLET” edge “v_edge.22”
“edge.14”
save
export fluent5 “rohr-diss-2d.msh” nozval
```

The grid thus created has a size of a little less than 34,000 cells. The data are exported into a mesh file that Fluent© can interpret and process. Fluent© reads the information from the file and requires additional information for the execution of the simulation. The steps to be followed in preparing the simulation are:

- Read the grid file and check it.
- Select the default segregated solver.
- Define the physical models.
- Specify the fluid properties.
- Specify the boundary conditions.
- Save the problem setup.
- Initialize the solution.
- Calculate the solution.
- Save the results.

The following menu points need to be filled in Fluent©:

Define->Models->Solver->Solver->Segregated

Define->Models->Solver->Formulation->Implicit

The explicit solver formulation was originally designed specifically for incompressible flow (1.6), but for the VOF-model a coupled solver is unavailable.

Define->Models->Solver->Space->2D

The computational domain is in 2D.

Define->Models->Solver->Time->Unsteady

The simulation is monitoring changes over time.

Define->Models->Solver->Transient Controls->[blank]

No transients occur in the simulation.

Define->Models->Solver->Velocity Formulation->Absolute

The absolute velocity formulation is preferred in applications where the flow in most of the domain is not rotating.

Define->Models->Solver->Unsteady Formulation->First-Order-Implicit

Define->Models->Solver->Gradient Option->Green-Gauss Cell Based

Define->Models->Solver->Porous Formulation->Superficial Velocity

Define->Models->Multiphase->Model->Volume of Fluid

Define->Models->Multiphase->Number of Phases->2

Define->Models->Multiphase->VOF Parameters->VOF Scheme->Implicit

Define->Models->Multiphase->Body Force Formulation->Implicit Body Force

Define->Models->Viscous->Model->k-epsilon

The simplest model of turbulence, used for a wide range of practical engineering flows.

Define->Models->Viscous->Model->k-epsilon Model->Standard

Robust, economical, and reasonably accurate standard k-epsilon model make it useful for a wide range of turbulent flows in industrial flow simulations.

Define->Models->Viscous->Model->Near-Wall Treatment->Standard Wall Functions

This option is most widely used in industrial flow simulation and is the default setting in Fluent©.

Define->Phases->Primary Phase->air

Air is the primary phase in the empty pipeline.

Define->Phases->Secondary Phase->water

Water is the secondary phase entering the empty pipeline.

Define->Operating Conditions->Gravity->y: -9.81 m/s

Gravitational acceleration acting in negative y-direction.

Define->Boundary Conditions->Velocity Inlet

Velocity Inlet is intended for incompressible flow.

Define->Boundary Conditions->Pressure Outlet

Solve->Controls->Solution->Under-Relaxation Factors

Pressure: 0.3

Density: 1

Body Forces: 1

Momentum: 0.3

Volume Fraction: 0.2

Turbulence Kinetic Energy: 0.3

Turbulence Dissipation Rate: 0.3

Turbulent Viscosity: 1

For the VOF-Scheme the Under-Relaxation Factors for all variables should be set to values between 0.2 and 0.5 for improved stability.

Solve->Controls->Solution->Pressure-Velocity Coupling->PISO

The PISO scheme is recommended for transient calculations in general. Using PISO allows for increased values on all under-relaxation factors, without a loss of solution stability. You can generally increase the under-relaxation factors for all variables to 1 and expect stability and a rapid rate of convergence.

Solve->Controls->Solution->Discretization

Pressure: Standard

Momentum: First Order Upwind

Volume Fraction: First Order Upwind

Turbulence Kinetic Energy: First Order Upwind

Turbulence Dissipation Rate: First Order Upwind

Solve->Monitors->Residual->Convergence Criterion

continuity: 0.01

x-velocity: 0.005

y-velocity: 0.005

k: 0.01

epsilon: 0.005

vf-water: 0.005

Solve->Iterate->Time Step Size: 0.0001 s

The maximum time step size for which the solution remained comfortably stable within 10 to 20 iterations per time step.

Solve->Iterate->Iteration->Maximum Iterations per Time Step: 40

The simulation of the rubber-hose experiment with the above parameters succeeded within roughly one week of computation. The computation of a full-scale aqueduct pipeline presented a new challenge. The first simulation investigated the pipeline at Aspendos. The primary difference between the hose model and the model of an aqueduct, apart from the size of the computational domain, is the ratio between length and width of the model. While the hose has a length of some 5 m and a width of 0.05 m (*i.e.* a ratio of 100), the Aspendos aqueduct pipeline has a length of 1,760 m and a pipe diameter (or width in 2D) of 0.28 m (*i.e.* a ratio of 6,286). Although the number of mesh cells in the computational grid (57,900 cells) of the aqueduct was not unreasonable, the calculations took a very long time, and the simulation of the complete filling process of the aqueduct was not complete by the end of this project. The water reached only the bottom of the first downward ramp. Experience has shown that it was unwise to begin the investigation with a full-scale model of the aqueduct at Aspendos. The computation time was in the order of eight weeks before the decision was made to interrupt the experiment because of the extremely long duration. A new simulation was started, in which the horizontal stretches of the aqueduct were reduced by the factor 1/20. The restart of the simulation of the smaller model showed quickly that the computation time was still in the order of months. As a third step, the length of the entire line was reduced in size once again by a factor of 1/10, maintaining, however the pipe diameter at 0.28 m and maintaining the original size of the header tank and the intermediate tanks on top of the towers at a scale of 1:1.

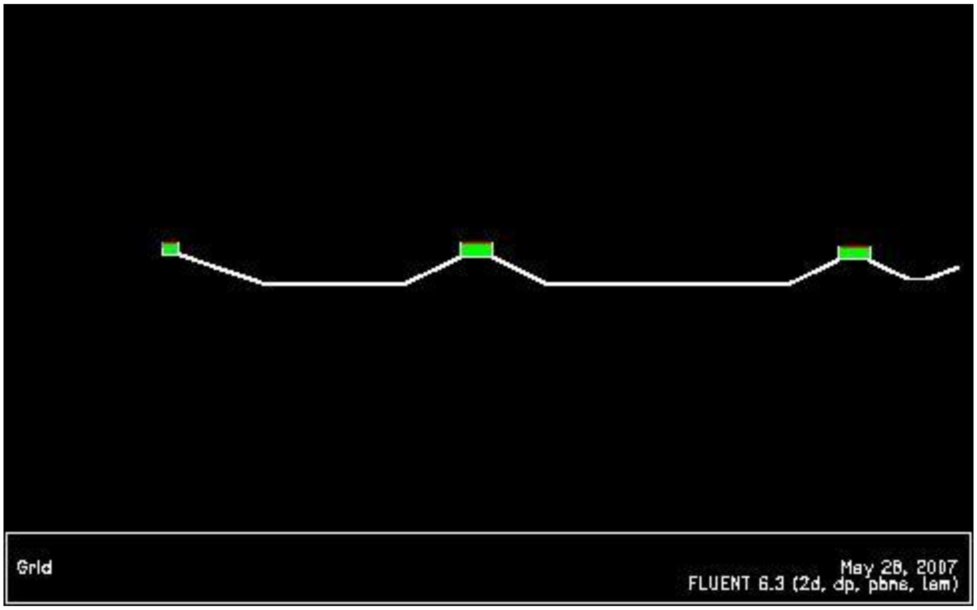

Figure 15.7: Aspendos 2D Geometry in Reduced Scale

The third restart of the simulation was interrupted numerous times due to hardware malfunctions of a new computer cluster with faulty components, due to regular computer maintenance procedures, and due to prioritizing of jobs on the part of the system administrators. By the time of writing this chapter the simulation of the model in 1:10 scale was still ongoing, but had not yet reached the advanced stage of the first attempt in which the water had reached the first horizontal stretch of pipe. The following images are results of the first simulation that was performed with the full-size model of the pipeline at Aspendos.

The following are snapshots of the filling process of the header tank of the aqueduct at Aspendos. Water (yellow) is entering the tank from the top half of the left vertical edge. The computational mesh is refined by a factor of two near the interface of water and air (red) in order to represent that region of interest in more detail.

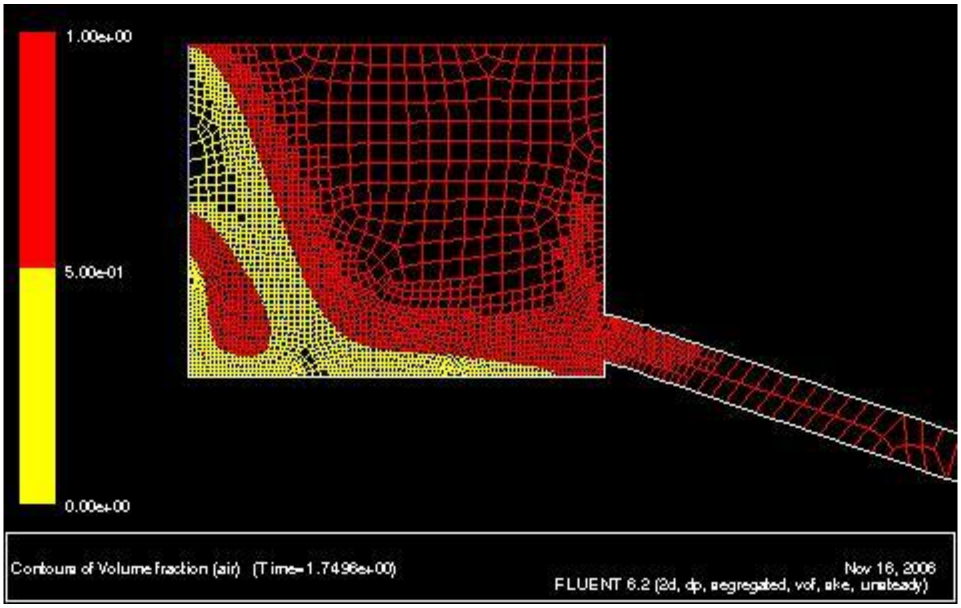

Figure 15.8: Inflow of Water in Header Tank at Aspendos (t=1.75 s)

Figure 15.8 shows the water entering the header tank from the top half of the left edge with a flow velocity of 1 m/s. The image shows the water impacting the floor of the tank at t=1.75 s. The water splashes forward towards the pipe entrance and backward up the rear wall.

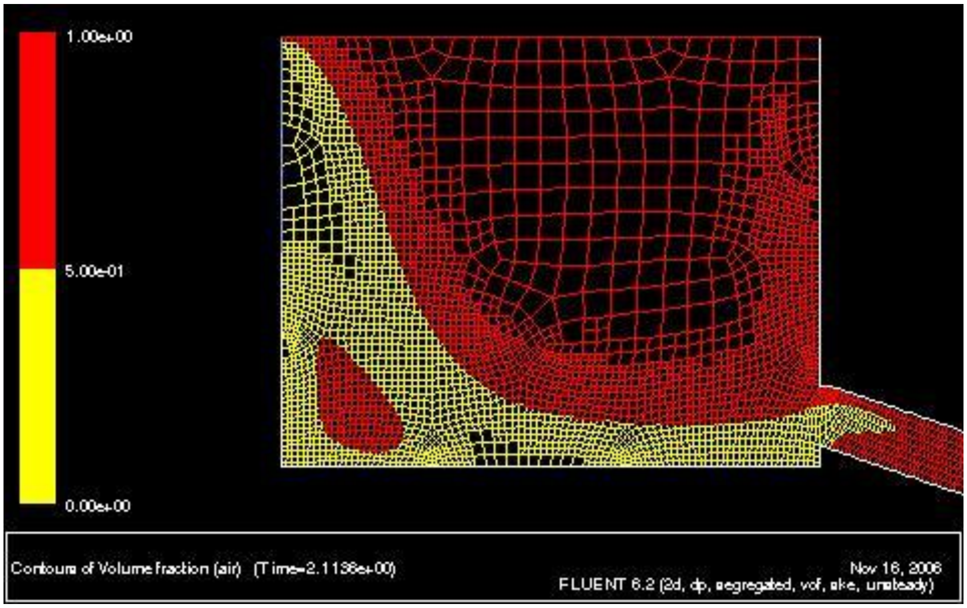

Figure 15.9: Water Enters the Pipe from Header Tank (t=2.11 s)

Figure 15.9 shows the water at the point of entering the pipe at t=2.11 s. The water forms a clockwise rotating vortex in the bottom left corner of the tank, while it enters the pipe in the bottom right corner. The front of water entering the pipe splashes upwards and will briefly occupy the entire cross-section of the pipe, forming temporarily a liquid piston moving along the pipe. This quantity of water will push the air that occupies the pipe ahead and will also suck in air from the header tank.

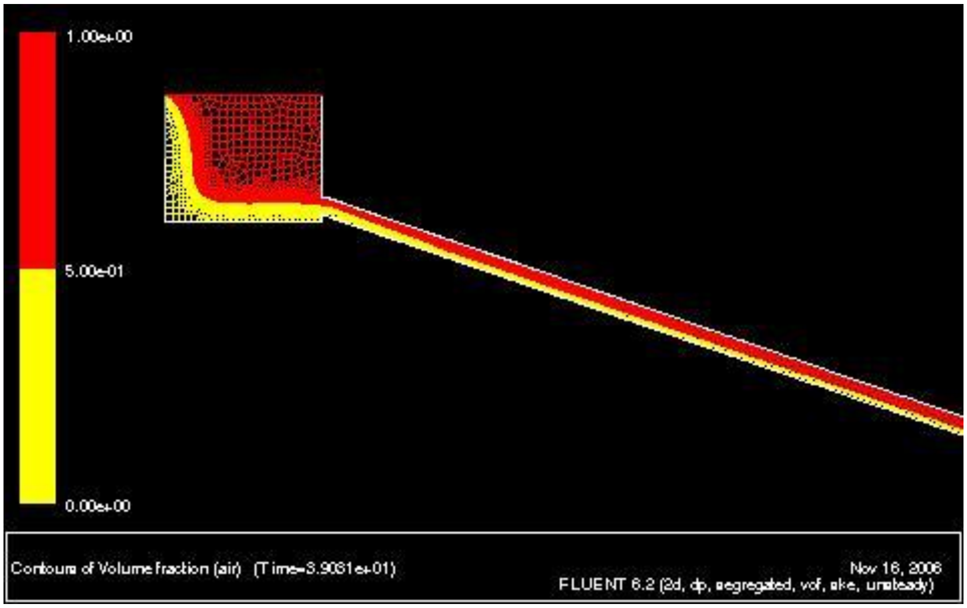

Figure 15.10: Established Inflow (t=39 s)

Figure 15.10 shows the water flowing down the first downward branch of the pipe at t=39 s. At a flow velocity of 1 m/s the water flows down the pipe without filling the full cross-section. The air in the pipe, displaced by the inflowing water should be, therefore, theoretically able to escape in both the downstream and the upstream direction. Figure 15.14, however, shows that the velocity vectors of the air above the layer of inflowing water are pointing downward, parallel to the flowing water. It is evident that the inflowing water is sucking air from the header tank into the pipe at a speed that is ten times higher than that of the water itself (*ca.* 15 m/s; *cf.* Figure 15.11). This phenomenon is due to the water front that initially occupied large part of the pipe cross-section.

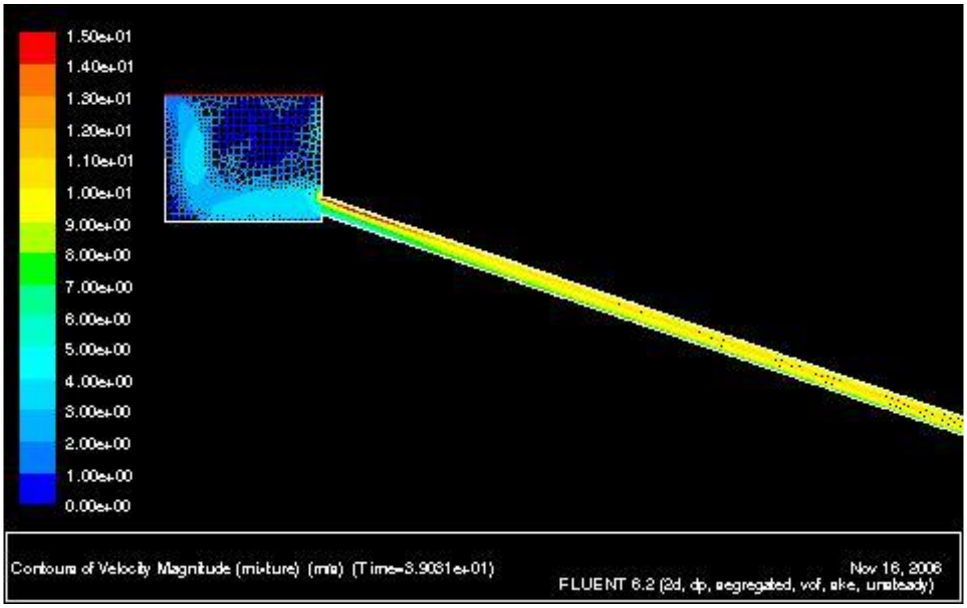

Figure 15.11: Flow Velocity of Air and Water (t=39 s)

Figure 15.11 shows also that the water, once in the pipe, is accelerated by gravity and flows downward with a velocity of up to 8 m/s until the force due to gravitational acceleration is balanced by the friction of the water with the pipe wall. This gradual acceleration of the water layer causes the water phase to thin out in the direction longitudinal to the pipe axis. Hence the air can occupy more space and decelerates to approximately the velocity of the flowing water. The velocity profile at the bottom right edge of the image shows no appreciable difference in velocity between the liquid and the gas phase. The flow velocity of both phases stabilizes at ca. 10 m/s.

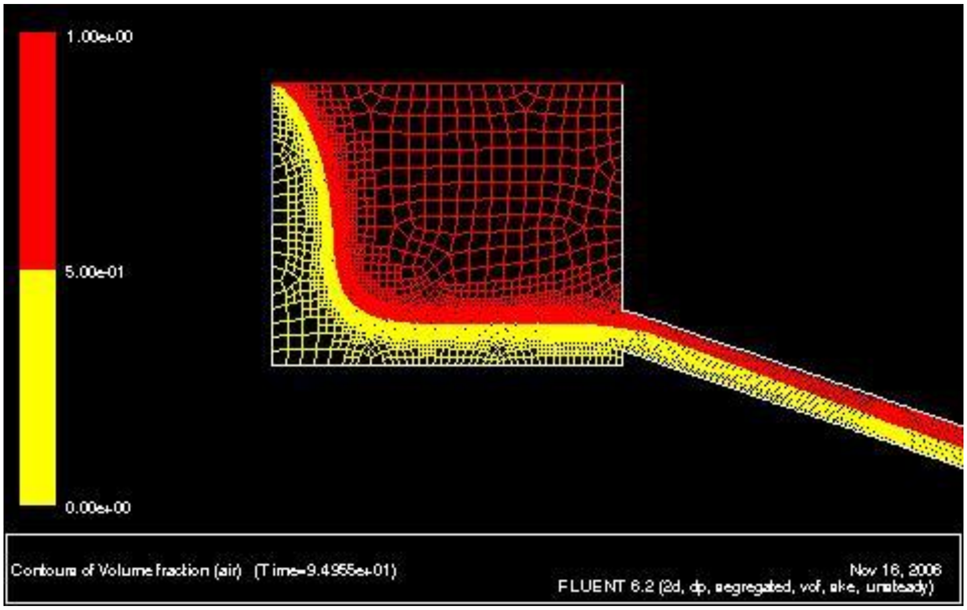

Figure 15.12: Established Flow Close-up (t=94.96 s)

Figure 15.12 shows a close-up of the established flow regime at t=94.96 s. The water flows into the header tank with a constant velocity of 1 m/s and enters the pipe. At this point in time the profile of the flow regime in the header tank is stable. The capacity of the pipe is sufficient to accept all water that flows into the header tank. This situation is, of course, true only in 2D, or in 3D only if the width of the pipe is equal to the width of the incoming open channel. In reality the width of the incoming free-surface channel is unknown, and the pipe diameter is 0.28 m. This result is, therefore, of only limited validity. It shows, however, that the Roman designers would have been able to observe easily if the pipe diameter was sufficient to admit all water flowing into the header tank. If the inflow was so high that the water level in the header tank rose above the upper perimeter of the pipe (and eventually overflowed at the header tank), it would have been possible to reduce the flow rate of the water to a point where the pipe would have been able to accommodate the complete inflow.

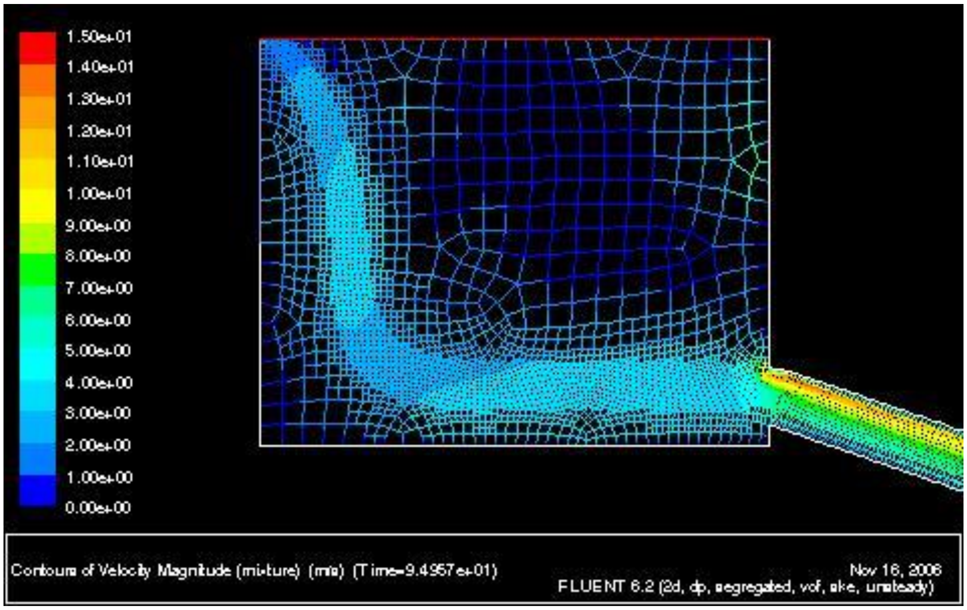

Figure 15.13: Flow Velocity of Air and Water Close-up (t=94.96 s)

Figure 15.13 shows a close-up of the velocity profile at a point in time when the flow was stable at the transition from header tank to pipe. The flow of air above the water has remained at approximately 15 m/s, though the front of water flowing down the pipe will have thinned considerably, so that the piston-effect would have been somewhat reduced. Close to the mouth of the pipe, the liquid and gaseous phases are distinguishable in the velocity profile. The top layer of water, furthest from the bottom pipe wall, flows with a velocity of *ca.* 9 m/s. Figure 15.14 is a more detailed close-up of the transitional area between header tank and the mouth of the pipe with the velocity represented as coloured vectors, showing largely the same situation as Figure 15.13 at the same point in time (t=94.96 s).

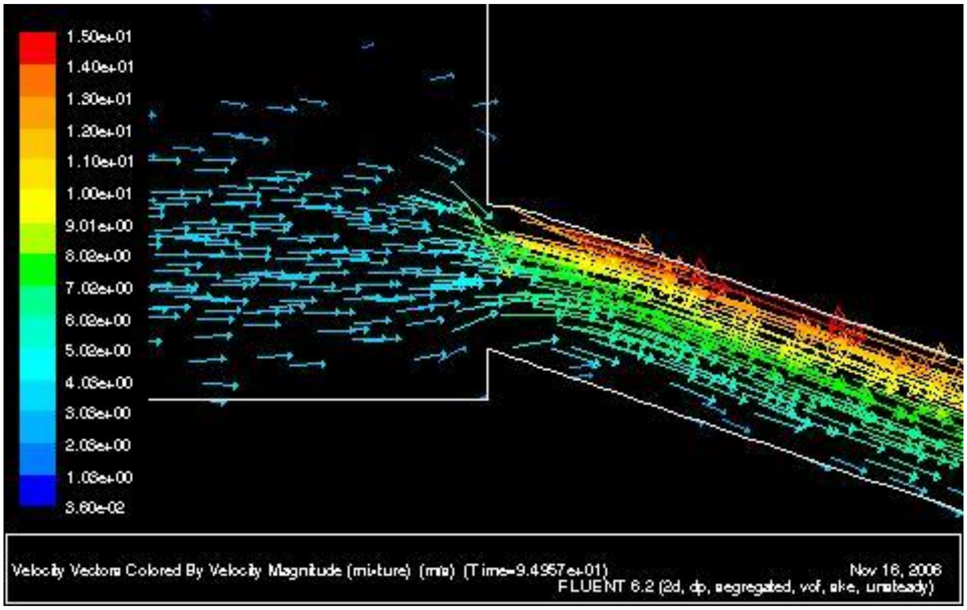

Figure 15.14: Velocity Vectors Close-up (t=94.96 s)

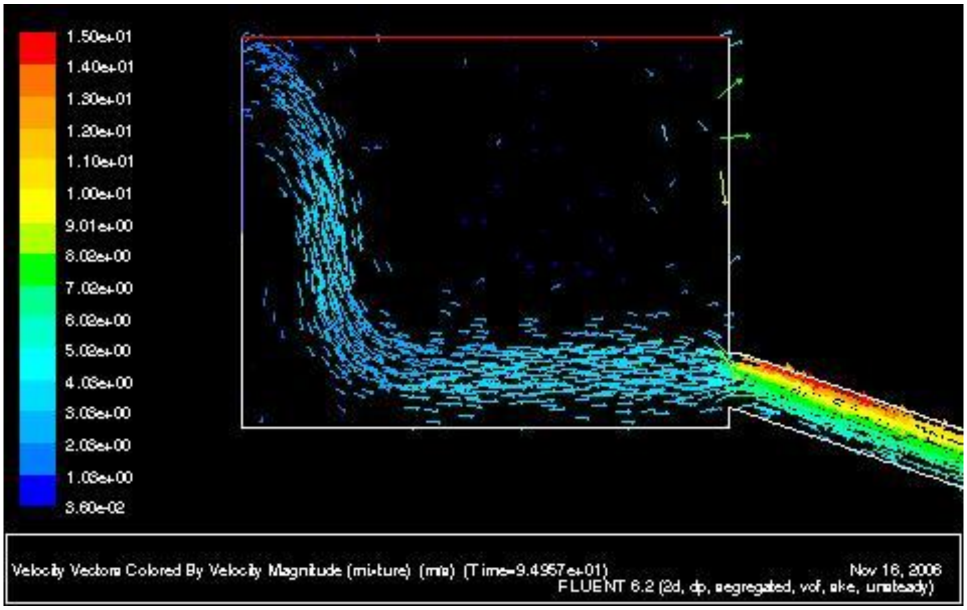

Figure 15.15: Velocity Vectors (t=94.96 s)

Figure 15.15 shows the same situation as Figure 15.13, but instead of velocity contours, the flow regime is represented in velocity vectors, showing the flow direction as well as the velocity magnitude.

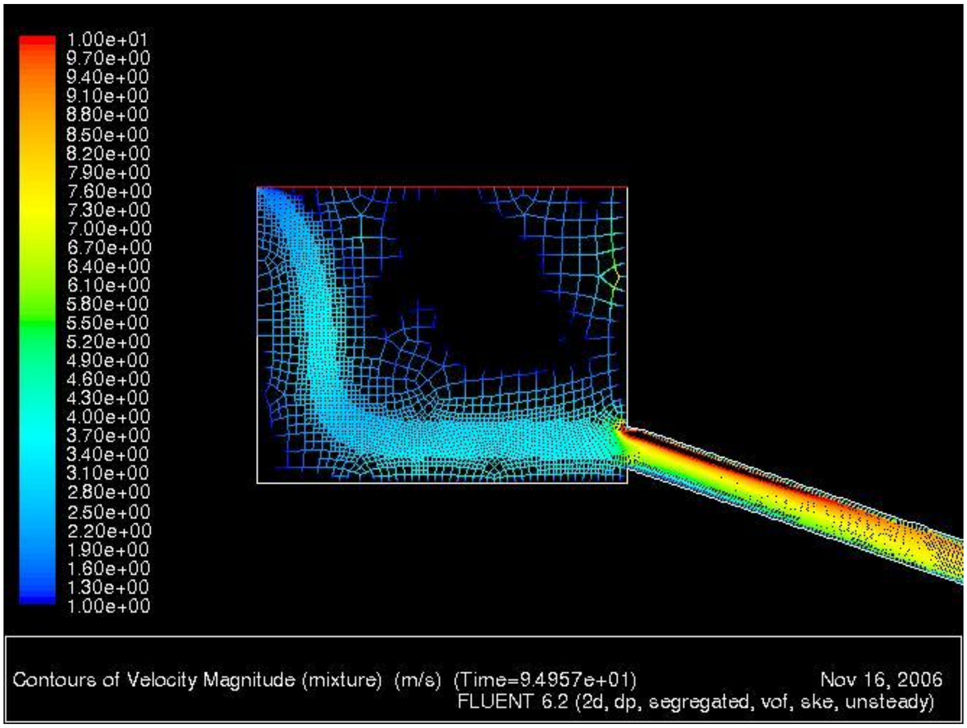

Figure 15.16: Flow Velocity Air and Water (t=94.96 s)

Figure 15.16 shows once again the same situation as the previous three Figures. The velocity magnitude is shown in coloured contours, with flow regimes below 1 m/s (black areas in the header tank) and above 10 m/s (black streak at the top perimeter of the pipe) cut out. This view shows, therefore, the areas of minimum and maximum velocities blank.

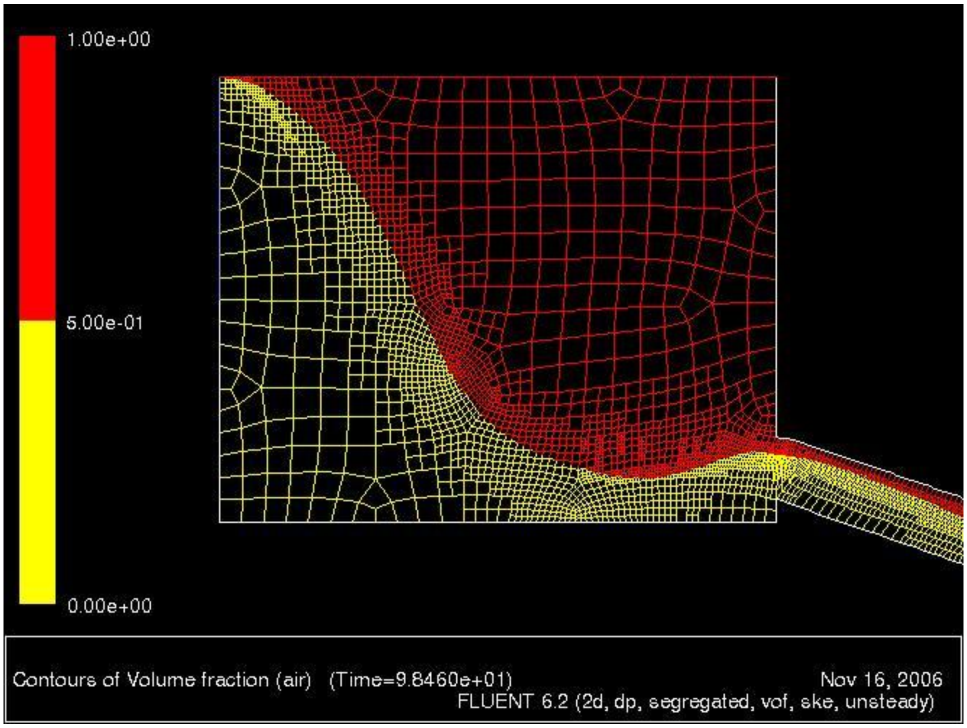

Figure 15.17: Flow Pattern After Temporary Acceleration to 2 m/s (t=98.46 s)

During the simulation the inflow of water into the header tank was temporarily accelerated to 2 m/s in order to investigate the influence of fluctuations of flow rate on the behaviour of the water at the pipe intake. The water level rises, as expected.

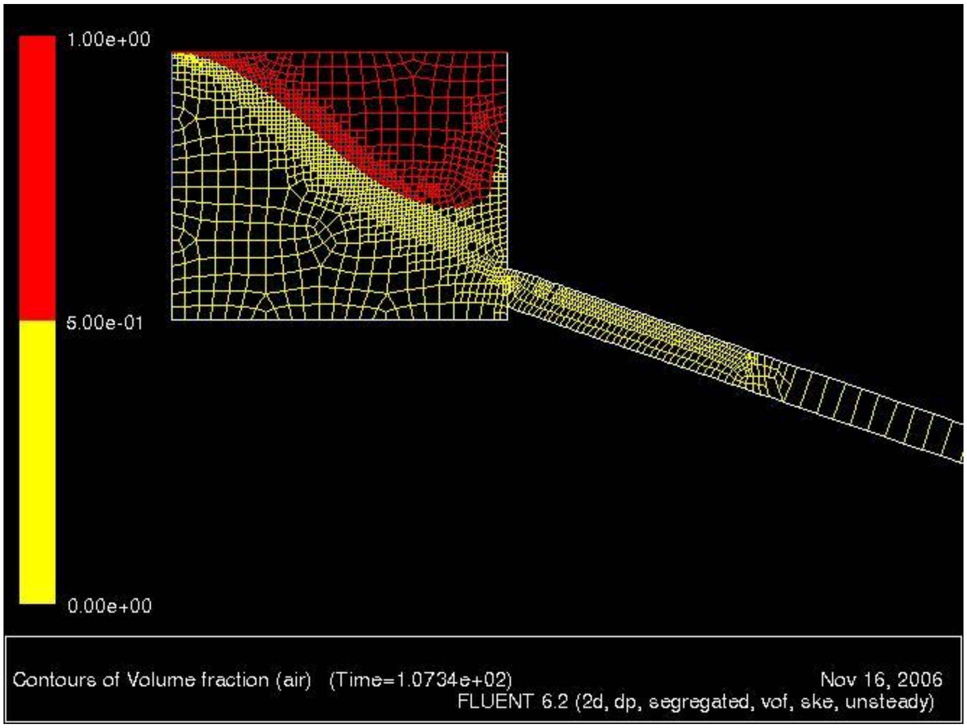

Figure 15.18: Flow Pattern After Temporary Acceleration to 2 m/s (t=107.34 s)

A flow velocity of 2 m/s is too large for the pipe to admit all the water. The water level, therefore, rises above the upper perimeter of the mouth of the pipe (Figures 15.17 and 15.18). Under this condition the header tank would eventually overflow, and the entire cross-section of the pipe is filled with water. The effect of the full-flowing pipe on the air ahead of the water front is unknown, as the computational grid was not dense enough to produce a meaningful result. It is clear, however, that the designers of the aqueduct must have had a provision either for safe overflowing of the water from the header tank or for regulating the inflow into the tank. Such provisions are very important, as there would have been a high danger of erosion by the overflowing water, which otherwise might have damaged the fabric of the header tank.

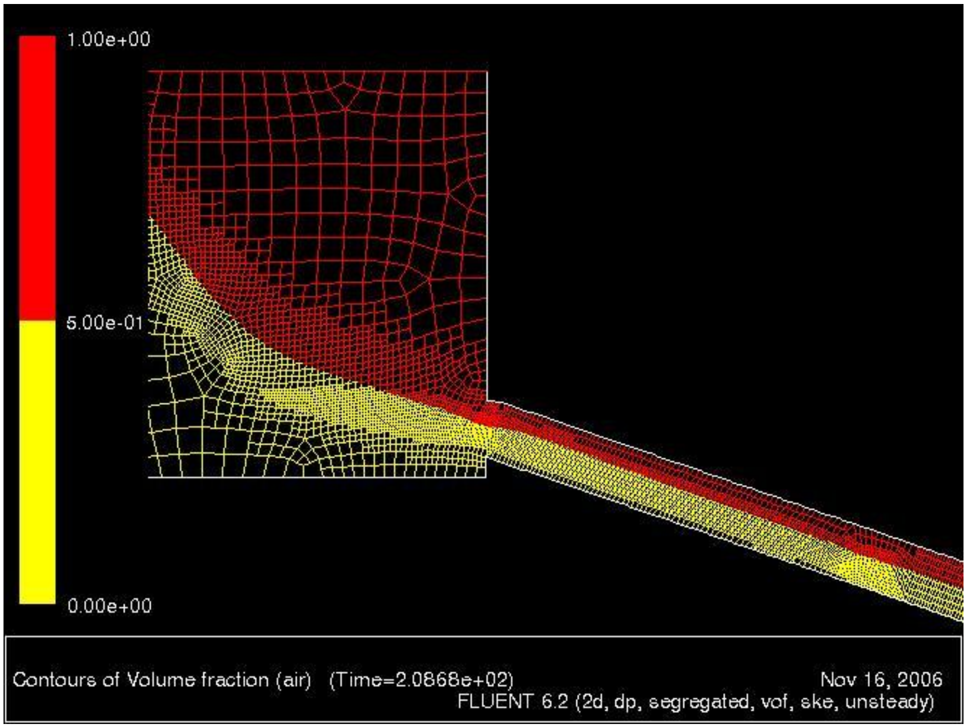

Figure 15.19: Established Flow Close-up After Deceleration to 1 m/s (t=208.68 s)

The flow velocity was reduced to 1 m/s again. At t=208.68 s the previous, stable flow regime reestablished itself (Figure 15.19). The pipe was again filled to only part of its cross-section with a bulb of water occupying the full diameter traveling downward. Again, this result in 2D is not immediately transferable to 3D, as the width of the circular pipe in reality would not have been the same as the width of the rectangular inflow channel.

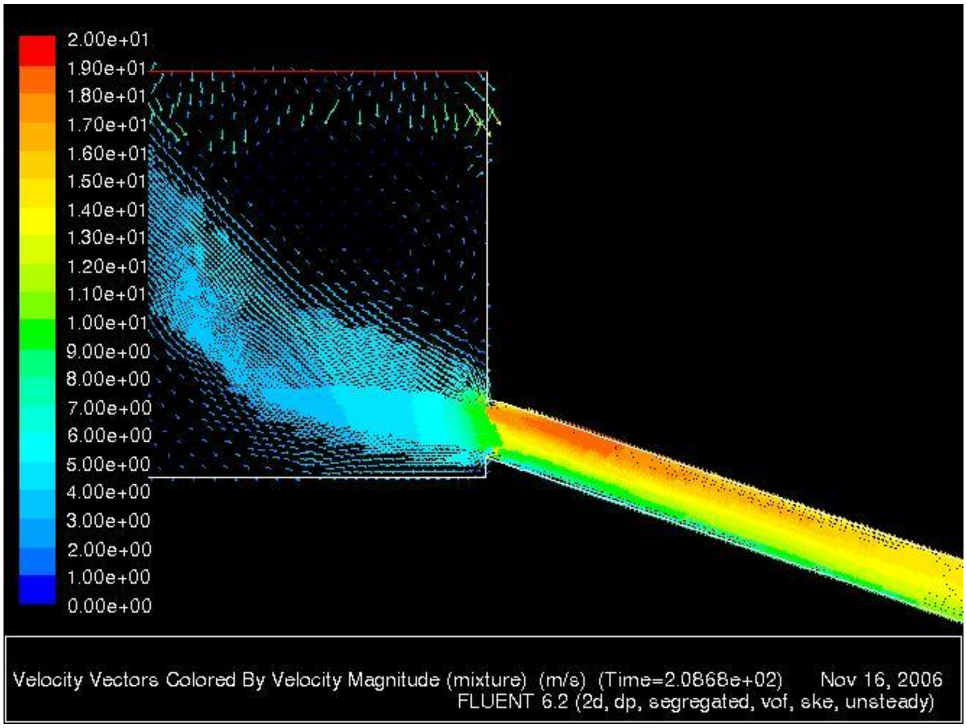

Figure 15.20: Velocity Vectors (t=208.68 s)

The flow velocity of the air in the top section of the pipe increased to 20 m/s after the deceleration of the water inflow into the header tank (Figure 15.20). The thinning bulb of water that is traveling downward through the pipe acts again like a piston that sucks the air into the pipe above the water layer. All the described phenomena occurred in the pipe before the water reached the first elbow at the bottom of the first downward incline of the pipe. The simulation was interrupted due to problems arising from inadequate mesh density further downstream of the first elbow, so that later results from this particular simulation were no longer meaningful.

Subsequent simulations were fraught with problems due to long computation times and due to hardware changes and ensuing problems. In an experimental project such problems are not uncommon and are part of the process. The following images show preliminary results from a simulation of the pipeline at a horizontal and vertical scale of 1:10 and a pipe diameter of 0.28 m. The flow velocity at inflow was 1.5 m/s. The images show the early filling process at t=2.56 s, *i.e.* unsteady flow. While they are not immediately relevant to the question of air bubbles in the pipe, they nonetheless show the potential of the method, provided that the simulation is brought to an end.

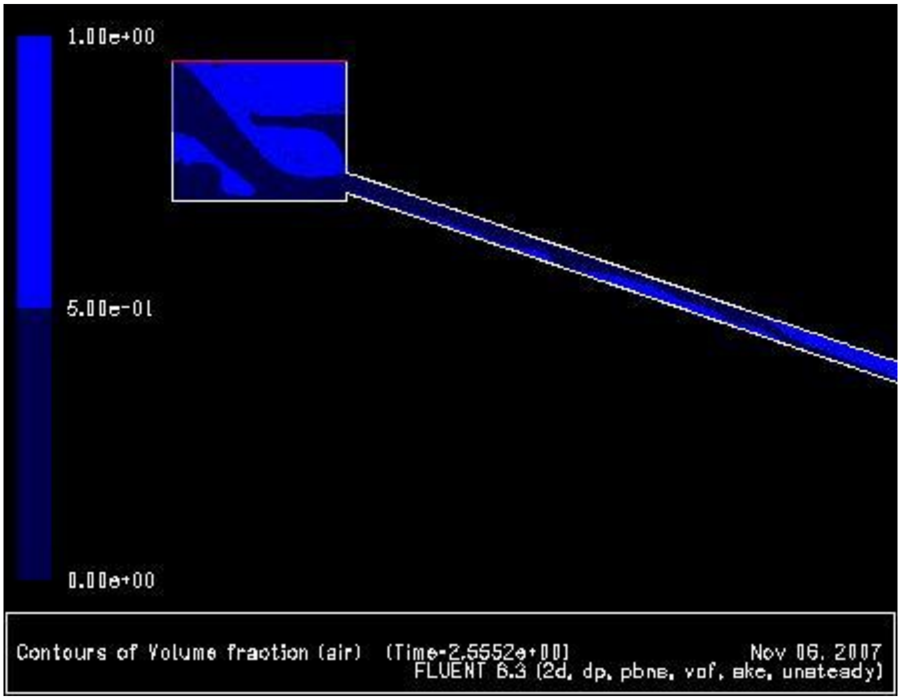

Figure 15.21: Volume Fraction Air (t=2.56 s)

Figure 15.21 shows a significant amount of sloshing in the header tank, compared to Figure 15.9, where the velocity at inflow was only 1 m/s. The water hits the floor of the header tank and from there enters the pipe at the top perimeter. It then descends to the pipe bottom after it has traveled a distance of approximately 3 m downstream.

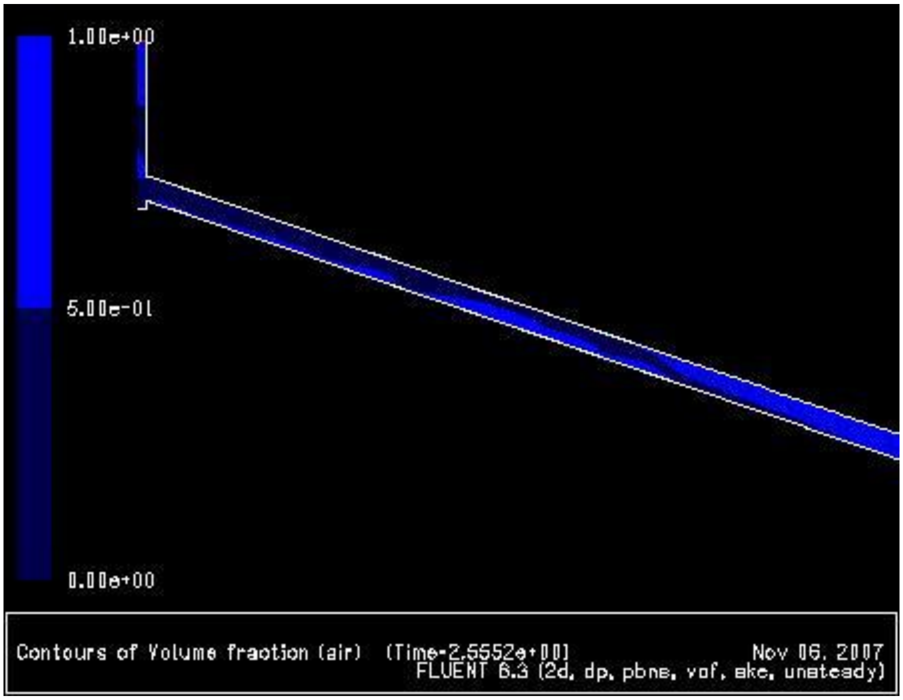

Figure 15.22: Volume Fraction Air (t=2.56 s)

Figure 15.22 shows a close-up of the pipe section where the water descends during unsteady flow from the top perimeter to the bottom perimeter of the pipe. It is visible that at t=2.56 s the water fills the complete cross-section of the pipe at the mouth. This means that the air that initially occupies the pipe is displaced downward and would be compressed if the tank on the intermediate tower were not open to the atmosphere. At a later point in time, as steady state condition is established in the flow at the mouth, it might be expected that the water will fill the pipe only part way at the bottom perimeter, so that air from the pipe will be able to escape upwards in the opposite direction of the flow of water. Figure 15.14, however, shows the opposite. The air above the inflowing water is accelerated downwards, and a suction effect is created that draws more air into the pipe. Only once the bottom of the pipe is completely filled with water, will the rising interface between water and air slowly push the air upwards out of the pipe.

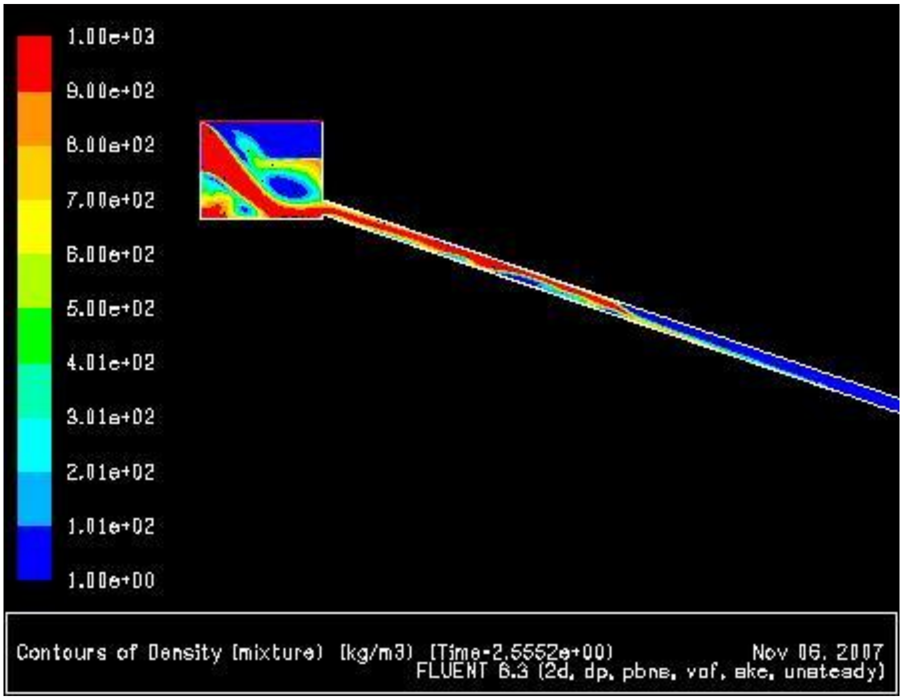

Figure 15.23: Density Contours (t=2.56 s)

Figure 15.23 shows a different view of the inflowing water, representing not the phases (liquid *vs.* gas) but rather the density of the two fluids. This representation would be useful for the investigation of potential pressure waves in the residual air.

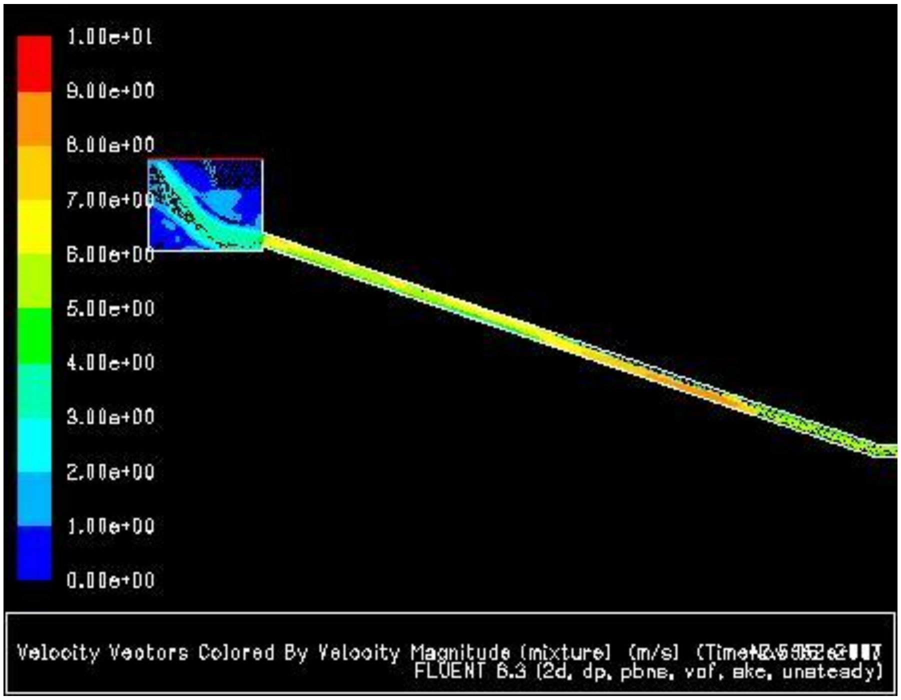

Figure 15.24: Velocity Vectors (t=2.56 s)

Figure 15.24 shows, like Figures 15.14, 15, and 20, velocity vectors (*i.e.* direction and magnitude of flow velocity) of the fluids in the pipe at an early point in time (t=2.56 s) for a flow velocity of 1.5 m/s at the inflow into the header tank. The representation shows that the water, as it flows down the pipe, is accelerated by gravity to a flow velocity of close to 9 m/s. It will be instructive to see the water hit the first elbow and evaluate the forces acting on the elbow due to the change in impulse.

Despite the numerous and ongoing technical problems and interruptions, the methodology of investigating the interaction of air and water in a pipeline by means of computer simulation was highly successful. The method shows great promise for the future, as computer speed is expected to increase and the user’s familiarity with the software will improve. The problem with inadequate mesh density, for example, has been noted and can be easily corrected in the future. It is important to keep in mind that these simulations are only the first steps into this type of archaeological research. Despite the caveat of the incomplete filling process of the aqueduct system, the results of the hose simulation and of the detailed investigation of the transition from the header tank to the pipe in 2D show that the chosen method is viable and can be expanded in the future as the experiences gathered from these preliminary computations are incorporated into future model design. The time constraints of the dissertation project do not allow further corrections and adjustments of the simulation. Nonetheless, the simulation was successful with respect to proving the viability of the research method, which holds the promise of more relevant results in the future. The 2D geometry of the pipeline at Segóbriga at a scale of 1:20 has been created and meshed, and is ready for simulation, as the research project will continue beyond the dissertation (Figure 15.25).

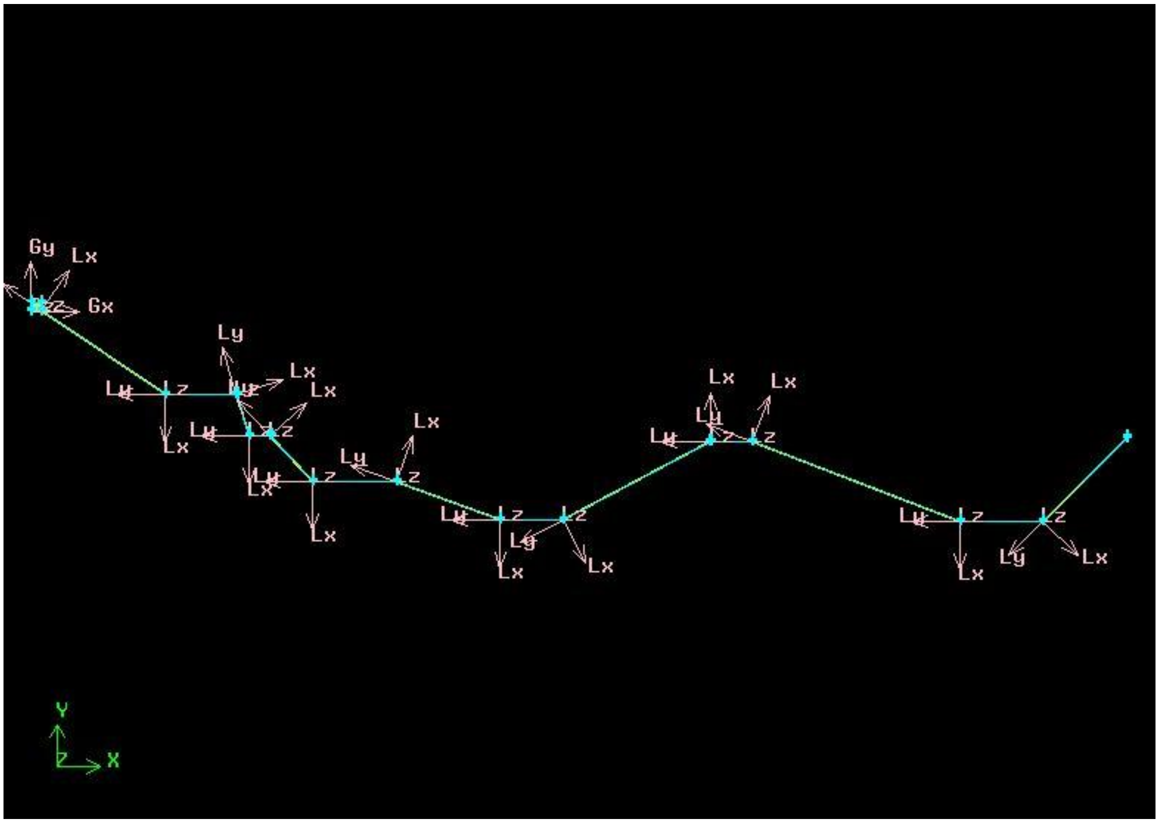

Figure 15.25: Segóbriga 2D Geometry in Reduced Scale, Showing Necessary Local Coordinate Systems

Other possible applications of the method have been demonstrated by Ortloff (1998) in his investigation of a drainage outlet at Priene. The investigation of water supply components by CFD-software is extendable to smaller systems, such as fountains or latrines, but with sufficient computational capacities also to complete urban distribution networks. Resulting flow rates, velocities, and pressures can provide valuable information about population sizes or generate detailed water usage patterns over certain periods of time. Future research ought to include the testing of other commercial CFD-packages and programming of new CFD-codes to match the specific requirements of the desired individual investigation.

16. Interpretation and Conclusion

The city was one of the fundamental institutions in classical antiquity. The Hellenistic kings who ruled the successor states of Alexander's empire were generous benefactors to the cities whose overall freedom as formerly independent polities was significantly reduced under the new political realities. This generosity found expression in lavish urban building programmes that proclaimed the greatness and stability of the ruling dynasties. The Hellenistic city was a suitable carrier for propaganda. In the cities of Asia Minor in particular, with plentiful financial resources and a tradition of oriental monumentality, extensive building profoundly transformed the cityscape. In a period of political volatility the defensibility of a city was very important, so they were frequently located on hilltops. The ability to withstand sieges is a primary concern of Hellenistic urban planning. The supply of the city with a sufficient amount of potable water formed part of this defensive strategy, illustrated by the Pergamene Astynomoi Inscription requiring citizens to keep the cisterns in the city clean and in a good state of repair (Klaffenbach 1954). Urban construction and development led to a population increase, leading to an increased demand for water that could no longer be satisfied by cisterns, wells, and local springs. The climate data for the Mediterranean cities show clearly that availability of fresh water must have been a problem, especially during the arid summer months. The logical consequence was the construction of aqueducts that brought sufficient water to the city from further afield. Greek cities had a tradition from the Bronze Age onward of constructing pipelines to satisfy their water demand (Tölle-Kastenbein 1990: 85; Hodge 2000a: 40). Prominent examples are Minoan Knossos, Mycenaean Thebes, and the city of Athens under the Peisistratids (Tölle-Kastenbein

1991). The state-sponsored technological advances during the Hellenistic period, illustrated by the work of, for example, Ctesibius, Philo of Byzantium, Archimedes, or Hero, allowed the construction of bold structures, among which were also spectacular aqueducts. These aqueducts were not only structures that made life in the hilltop cities significantly more comfortable, but were also outstanding symbols of the wealth, power, benevolence, and durability of the rulers. The Madradağ pipeline, for example, presumably terminated at the Pergamene Royal Palace—a worthy end point for such a representative piece of construction. The aqueducts had, therefore, a strategic, a logistic, and a symbolic dimension. Lewis (1999: 157) calls them "a phenomenon of the Hellenistic period."

Pipelines were preferred to channels in Hellenistic aqueducts for several reasons: first, Greek aqueducts consisted traditionally of pipelines because they were easily concealed underground and did not present a convenient target for sabotage in a period of frequent warfare. Second, the hilltop location of cities often did not offer an alternative to inverted siphons, which require pipelines. The elevations of Pergamum (*ca*. 300 m above the surrounding land), Smyrna (*ca*. 200 m above the surrounding land), or Methymna (*ca*. 90 m above the surrounding land) were too high to allow water supply by means of open channels on arcaded bridges, even if that technology had been widely used by the Greeks. Third, the pipelines were usually made of terracotta, a material that was relatively inexpensive, allowed pipe segments to be mass-produced off site, and in the production of which the Greeks had been masters for centuries. If a technology works well for a long time and for which significant know-how is available, there is no need to depart from it; small modifications are sometimes necessary to adapt to exceptional circumstances, as presented themselves at Pergamum and Smyrna. The elevation of the cities demanded that the designers of the aqueduct push the boundaries of a familiar technology. Pergamum had been supplied with water from pipelines (the Attalos and Demophon aqueducts) prior to the construction of the Madradağ aqueduct, albeit ending at elevations below the hill summit. The chronology of construction of the six aqueducts supplying ancient Smyrna cannot be established, although it is probable that one or more of these aqueducts predate the construction of the spectacular Karapınar aqueduct. Lewis (1999: 161) suggests, based on the similarity in layout between the Madradağ pipeline and the Karapınar pipeline, that Pergamene architects helped construct the latter, drawing on the rich experience from the construction of their own water supply systems. This assessment is conjectural and, because of the different building material, lead in Pergamum, terracotta and stone in Smyrna, problematic. While it is true that the Attalos pipeline, too, consisted of terracotta and stone pipe segments, one would expect that for an inverted siphon so close in size to that of the Madradağ aqueduct Pergamene designers would once again have preferred lead to terracotta as building material. The decision to direct the pipeline across intermediate hills need not necessarily point to the same designer. It is rather a solution that emerges logically for pipeline construction in a tectonically active region. Once it was noted that a pipeline was damaged or destroyed by a mudslide or an earthquake it would have been readily apparent, without extensive transfer of know-how between cities, that it is wiser to cross topographic contour lines at right angles rather than to locate such a heavy cylindrical structure parallel to the slope. Greek cities, like Miletus or Priene, had for centuries been laid out on a grid pattern even in very sloping terrain, so that there was certainly sufficient experience in western Asia Minor to know how to secure heavy objects with minimum expense against downslope dislocation. The Smyrneans, therefore, would not necessarily have required Pergamene know-how for the construction of an aqueduct. Contrary to Lewis' assessment, the different building material used on the Madradağ and the Karapınar aqueducts—lead *vs.* terracotta and stone—rather seems to suggest different designers. The two inverted siphons are structures developed independently in response to similar topographic circumstances.

The inverted siphon at Alatri is, in my opinion, likewise an independent development and need not be connected to either of the systems at Pergamum and Smyrna. Lewis (1999: 162) himself concedes the tenuousness of his argument that a monogram occurring on pipe stamps from the Madradağ aqueduct could be "resolved as A. ΒΕΤΙΛΙΗΝ" and hence establish a link between Pergamum and the family of the Betilieni from Alatri. It is true that the layout of the pipeline at Alatri is very similar to those at Pergamum and Smyrna. Once again, however, I suggest that it is the problem that dictates the solution, not an exchange of technical skill that originated at Pergamum. The town of Alatri is located on top of a hill, and the only viable solution to supply flowing water is through a pipeline. Italy, like Asia Minor, is a region with tectonic activity, so it is common sense to secure the pipeline against lateral dislocation by crossing the contour lines at right angles. It must be added, too, that this layout is Lewis' reconstruction based on Laurenti's (1987) article and on the examples from Pergamum and Smyrna. In Bassel's (1881b: 121; Merckel 1969: 561) original reconstruction, the pipe carefully avoids the summits of the intermediate hills. Given the geophysical conditions of the region, though, Laurenti's and Lewis' reconstruction is preferable to Bassel's. The date of construction of the Alatri aqueduct after the bequest of Pergamum to Rome seems to suggest conveniently that the Betilieni saw the Asian aqueduct as a model and followed the example by building a similar aqueduct in their home town. While such a scenario is not impossible, the evidence is not sufficiently pressing to accept a close original-and-copy relationship between the aqueducts at Pergamum and Alatri.

The aqueducts at Lyon and Segóbriga were built by the Romans in a period when Roman influence was expanding throughout the Mediterranean region. The aqueducts in the provinces were carriers of Roman culture as much as they were carriers of water. The climate data for Lyon, for example, show that the aqueducts were initially not a necessity of life in the region, although the site of the pre-Roman Lyon on Fourvière Hill is “pauvre en eau” (Burdy 2002a: 19). Less than 30 years after Lugdunum was founded in 43 B.C., the town became capital of the “Three Gauls”. Within a short time the population grew to several tens of thousands. This population needed to be supplied with drinking water, but at the same time the new capital required an infrastructure that befitted its new political and administrative status. Aqueducts were, of course, part of this infrastructure (Burdy 1991a: 7). All four aqueducts that supplied Lugdunum contained inverted siphons (a total of 9) because the lines had to traverse the crescent-shaped valley that cuts off Fourvière Hill from its western hinterland. The double inverted siphon of the Yzeron aqueduct follows an almost straight west-east line requiring the minimum possible length of piping. The intermediate high point at Craponne is not very prominent, so a relatively modest tower for venting the air block was constructed as an alternative to a more circuitous route of unknown length that would have avoided the high point. The portion of the inverted siphon upstream of the high point could have been avoided by building an open-channel bridge approximately 10-12 m high, but *ca.* 2 km long. In comparison, the inverted siphon at Aspendos, built entirely on an arcaded substructure of varying height (main bridge *ca.* 15 m high), is *ca.* 1.7 km long. This conclusion contradicts Smith (1976: 66), who states that the depth of crossing was the decisive criterion for choosing an inverted siphon over an open-channel aqueduct bridge, quoting a maximum height of *ca.* 50 m for an aqueduct bridge. He suggests that for a valley crossing shallower than 50 m the Romans would have preferred a bridge to an inverted siphon. The designers of the Yzeron aqueduct must have weighed the options and decided that the relatively small tower and 6-7 parallel lead pipes were the preferable alternative. There is general agreement in modern scholarship that cost calculations played a role in the choice of conduit type, although quantification is difficult (Fahlbusch 1982: 139-40; Leveau 2001). Leveau (2001: 94) came up with a cost of 2.25 million sesterces per kilometer of open-channel Julio-Claudian aqueduct in the city of Rome, Burdy (2002a: 187) with *ca.* 2 million sesterces for the same. No estimate exists, to the best of my knowledge, for the cost of lead pipeline. Hodge (1992: 156) states that the cost of the lead used at Lugdunum was “perhaps not prohibitive” and that the ancient world had a “positive glut” of lead as a by-product of silver production. Britain and Spain were the provinces most productive of lead (Hodge 1992: 466, n. 13). It is, therefore, no surprise that the aqueducts at Segóbriga and at Lugdunum consisted to a large extent of lead pipes. If a pipeline was the conduit of choice for the 2.2 km of aqueduct section that constituted the first part of the inverted siphon at Craponne, where an open channel on some substructure would have been technically feasible, then it is fair to say that the pipeline cost less than 5 million sesterces at Leveau’s 2.25 million sesterces per kilometer. The entire inverted siphon of the Yzeron line, at a length of *ca.* 6 km, would, therefore, have cost a maximum of *ca.* 13.5 million sesterces. This amount is almost 70% more than the 2 million denarii (or 8 million sesterces) donated by Tiberius Claudius Italicus for the aqueduct at Aspendos in the 2nd-3rd century A.D. Burdy (2002a: 187) suggests “avec les plus extrêmes réserves” a cost of 80 million sesterces for the whole 40 km of the Yzeron aqueduct, based on 2 million sesterces per km. Transport costs, in particular for overland transport, would have played a significant role in this calculation. The quarry where the building material for the Aspendos pipeline was cut is located in the immediate vicinity of the pipeline itself, which significantly reduced the overall building costs.

The aqueduct at Segóbriga was built in the early Principate during a period of heightened building activity in the town, recently after it had been accorded the legal status of *municipium*. The date of the aqueduct (1st c. A.D.) is close to the construction date of the Theatre Baths (under Augustus or Tiberius), so that the primary purpose of the aqueduct was likely the delivery of sufficient water to this bath complex. This development parallels quite closely the construction of the Aqua Virgo in Rome in 19 B.C. to supply the new Baths of Agrippa and the associated Stagnum, located between the Largo Argentina and the Pantheon (Evans 1994: 109; Aicher 1995: 39, 73). “Through this kind of ‘Romanization’ the Iberian élites were attracted into the Roman system of clientship” (Abascal, Almagro Gorbea *et al.* 2006: 190). The exact route of the pipeline at Segóbriga is, after that of Methymna, the least certain of the seven systems considered in this dissertation. The layout published by Almagro Basch (1976) is no longer considered correct. Moreover, the map scale was erroneous—an error that I first detected. A new suggestion for the aqueduct layout has not yet been published, and the information used in this dissertation was generously supplied by Professor Abascal in a personal communication. The aqueduct is unique because it consisted of a pipeline in its entire length. In the upstream part of the line water flowed with a free surface, while in the downstream part water filled the pipe completely and flowed under pressure. Almagro Basch locates the transition point at *ca.* 2.5 km from Segóbriga, although this distance could have varied significantly depending on the volume of water that came from the two sources, Fuente de la Mar and Fuente de las Zarzas. The minimum length of the inverted siphon, during a time of extremely low water volume supplied by the springs, would have been *ca.* 1 km, *i.e.* the distance between the receiving tank and the nearest point along the pipe with the same elevation on the opposite side of the depression. The intermediate high point at Segóbriga is relatively modest in height, but could not have been avoided due to the generally undulating nature of the terrain. Based once again on Leveau's figures for the Julio-Claudian period and the fact that the Romans preferred a pipeline to an open channel for the first segment at Yzeron, the 7 km of lead pipe would have cost a maximum of *ca.* 15.8 million sesterces, but probably significantly less because Segóbriga had only a single pipeline, while the Yzeron line had 6-7 pipes in parallel. Divided by 6, the amount shrinks to a maximum of *ca.* 2.6 million sesterces for a single pipeline of that length.

The inverted siphon at Aspendos is unique, although the aqueduct system is an example of civic munificence that was typical of the Asian cities in the Roman Empire. Non-hydraulic examples of civic munificence in Asia Minor are the Library of Celsus at Ephesus or the structures funded by Plancia Magna at Perge. An open-channel aqueduct for the final stretch north of the citadel of Aspendos was not an alternative, as its height would have had to be more than 40 m, almost as high as the Pont du Gard, the highest known Roman aqueduct bridge (48 m), although much longer (1.7 km *vs.* 275 m for the Pont du Gard). A pipeline was, therefore, the only reasonable alternative. Because of its two towers the inverted siphon at Aspendos belongs in the group of aqueducts with intermediate high points, but within the group it stands apart. While for the other systems the reasons for incorporation of high points are evident responses to topography and other geophysical conditions, the inverted siphon at Aspendos traverses a level plain without problematic terrain. The 1.7 km could have been crossed with a pipeline laid out on a relatively modest substructure. The purpose of the towers is not self-evident. No natural high points, such as at Craponne, would have caused an air block that needed to be vented. In fact, the towers themselves created the problem of air blocks and, therefore, required the open basins on top. Much emphasis in previous scholarship has been placed on the location of the towers at the prominent bends on the line. To be sure, elevating the water to the level of the hydraulic gradient eliminates lateral forces caused by static pressure, which may otherwise have led to displacement of pipe segments in these locations. The occurring forces, however, were not so large that they could not have been checked by anchoring the pipeline at ground level. If the towers were truly built for that purpose, they are awkward solutions indeed. Water hammer was certainly not a problem at Aspendos. It would not have occurred, because the line contained no stop cocks. Even had it occurred, the pressures would not have been so large as to be destructive to the stone pipes. Inverted siphons of much greater length and depth functioned without any evident provision against the effects of water hammer. It is unreasonable to suppose that this relatively modest structure at Aspendos would have been particularly at risk from water hammer when no other aqueduct elsewhere apparently was. The idea of water hammer is based on an erroneous interpretation of the Vitruvian phrase about the *vis spiritus*. Kessener (2000a: 126-8) does the right thing by employing fluid dynamics to solve the question, but the method he is using (Falvey 1980: 71) is not applicable to the case of lateral leaks in a pipeline.

Functionally the towers at Aspendos may be related to the example at Methymna. The tower at Methymna was built on an isolated hillock that could easily have been circumvented. The complicated arrangement of grooves, holes, and pipes in the tower, however, clearly indicates an intricate distribution system, suggesting that the hillock was a type of hub for the purpose of bringing water to different locations. No such evidence exists at Aspendos. Furthermore, the tower at Methymna brought water up and down vertically, very similar to the water towers at Pompeii, not obliquely over ramps, such as at Aspendos.

A point that deserves more attention than it has received in the past is the existence of the stairwells in each of the towers at Aspendos. I contend that the two stairwells might be closely related to the real purpose of these two towers, and that the purpose has nothing to do with hydraulics. For some reason it was necessary for people to ascend and to have access to water in that elevated position. Perhaps the towers were used as observation posts for guards overlooking from both sides the valley north of Aspendos. In time of war these guards could have been provided with hand-held catapults to defend the siphon—the most vulnerable part of the aqueduct—from interference. It is also possible that the two basins on the towers were places for the inhabitants of the adjacent plain to draw water. The inverted siphon took water from the hills to the north straight across the valley to the acropolis, and people on the plain would not have benefited from it. But such take-off points could have been realized more easily by branching smaller pipes off the main pipe by means of T-junctions at the level of the main bridge. Perhaps the towers were merely meant to be an extravagant monument commemorating the munificence of Tiberius Claudius Italicus. If the towers functioned as a prestige monument, they fulfilled their purpose magnificently, because they still provoke comment even today. Whatever the true purpose of the towers, and I suggest that the stairwells are related to it, the inverted siphon at Aspendos would have performed its function as aqueduct just as well—if not better—without the towers along its course.

By running the pipeline (deliberately or by necessity) across intermediate high points, the designers accepted the risk of air blocks. The calculation of the air bubble that would have formed during the filling process in the Yzeron aqueduct shows without a doubt that air blocks occurred, but the remains of the tower at Craponne also show that the designers knew how to solve the problem. The “Tourillons” demonstrate, moreover, the awareness on the part of the Roman designers of the hydraulic gradient, their ability to determine the gradient over long distances, and the understanding that the tower needed to be built up to the hydraulic gradient. Too high a tower would have completely interrupted the flow of water, too low a tower would have led to continuous loss of water and structural damage due to overflowing.

The following conceptual approach is conceivable in the construction of an inverted siphon. Every urban distribution system that uses a dendritic arrangement of *castella* from the primary distribution point at the highest elevation of the city to the final consumer is made up of a large number of inverted siphons. Urban distribution systems consisting of pipelines were in use for centuries before the construction of the spectacular long-distance water pipelines of the Hellenistic and Roman periods. Ancient designers were very experienced in this technology, probably learning more and more as the size of individual systems increased. The work of Hero shows that the behaviour of an air-water interface was well understood qualitatively and could be applied to various purposes. The description in the *Pneumatics*, written by Philo of Byzantium in the 3rd century B.C., of wine vessels maintaining a constant level of liquid by means of a submerged tube that communicates between two adjacent vessels shows that inverted siphons were used in small-scale technical applications already in the century before the construction of the large inverted siphon of the Madradağ aqueduct. The description of a force pump by the same author shows that positive displacement of fluids, too, was well understood and that the tradition of applying these particular hydraulic principles to practical purposes reaches well into the Hellenistic period (Hill 1979: 192-3; Oleson 1984: 51; Amedick 1998: 502 and 499, Fig. 6; Wilson 2002: 7).

The construction of a pipeline is relatively simple. The beginning must be higher than the end, and no point along the line may be higher than a straight line drawn between the starting point and the end point. Vitruvius expresses this requirement:

> Quodsi caput habeat libramenta ad moenia montesque medii non fuerint alteriores, ut possint interpellare, sed intervalla, necesse est substruere ad libramenta, quemadmodum in rivis et canalibus. (Vitr. 8.6.5)

> But if it has the head on the same level as the city walls and the hills between them are not higher so that they might interfere, but if there are valleys in between, it is necessary to build a substructure to the level in the same manner as for channels and canals.

The expectation is that what goes in at the beginning will come out at the end. Common sense dictates that contour lines be crossed at right angles. A pipe running parallel to the topographic contour lines is prone to damage for various reasons and requires a substantial substructure that must be built before the pipes can be laid, lengthening considerably the time frame of construction and increasing the financial expense. This problem was familiar in road construction, as well, but in that case the advantages of a level route outweighed the engineering costs (Quilici 2008).

At some point in time, perhaps in the Archaic period when water pipelines became common in Greek cities (Tölle-Kastenbein 1990: 85), one such brand new pipeline was filled and no water came out at the end. Instead, the water overflowed at the header tank. After what was probably a considerable shock, possibly in the presence of local dignitaries who may have assembled to witness the momentous inauguration of the new pipeline—on one such ceremonial occasion, the opening of the drainage tunnel at the Fucine Lake, the emperor Claudius nearly drowned (Suet. *Cl.* 32)—the crafty engineers would have tried to find the reason for the obstruction by drilling holes into the pipe to see where it was filled with water and where it was not. In that manner they would eventually have happened upon the air bubble downstream of a high point. As they drilled more and more holes into the bubble, they would have noticed that the air escaped and water occupied the vacated space. Eventually, sufficient air would have been vented from the pipe, so that the flow of water to the end of the pipe was established to everybody's satisfaction.

Gathering experience from a number of similar incidents the designers would soon have learned what feature of the pipeline caused the problem and where exactly the holes needed to be located to avoid such problems in future projects. Many pipe segments have been found with lateral holes in their walls (Stenton and Coulton 1986; Tölle-Kastenbein 1991). By lateral I mean at right angles to the pipe axis, *i.e.* these holes could occur in the side wall or in the top wall of the pipe. Notable examples of inverted siphons in situ where such holes occur mainly in the top surface of the pipe are Laodicea ad Lycum (Şimşek and Büyükkolancı 2006: 141) and Patara (Fahlbusch 1989: 228, 230). Both these inverted siphons have no intermediate high points. Pipe segments with holes at the top were found also in the urban distribution network of archaic Athens (Tölle-Kastenbein 1991: 27). At Laodicea and at Patara the lateral holes were used to drain the pipelines, when necessary, for maintenance or repairs. There is evidence that stretches of pipeline were exchanged at Laodicea (Şimşek and Büyükkolancı 2006: 140). For such procedures the inverted siphon had to be at least partially empty, depending on the position of the damage, and the only way to drain water completely from a sagging pipeline is by opening a valve or hole at its lowest point. "[Drain cocks] were probably simple holes in the siphon normally kept stoutly plugged and opened only to drain the siphon" (Fahlbusch 1982; Hodge 1983: 217). Fahlbusch (1982: 85), too, identifies these holes as drains. Stenton and Coulton (1986: 50) ask a valid question: If these holes were draining holes, "they should not occur well up above the top of the inverted siphon as at

Patara and Laodicea, and they should have been cut in the side of the pipeline not the top." The answer is simple. Not many aqueducts survive with the pipes *in situ*, so the exact orientation (side or top facing) and position of the segments within the line is often unknown. At Laodicea, the holes in the top face of the pipeline were located at intervals of *ca.* 25 m in the bottom stretch and at intervals of *ca.* 4 m at the ascending branch of the inverted siphon (Fahlbusch 1989: 230). The frequent holes in the sloping section were not used, however, to fill the pipeline with vinegar for chemical cleaning, as Fahlbusch asserts. It is necessary to drain an inverted siphon carefully. The typical water pressure available in modern household pipes is *ca.* 3 bar. Everybody who has drilled by accident into a modern pipe will know how violently the water shoots from the hole. If one simply opens holes at the bottommost point of an ancient pipeline, water will shoot out with a pressure of *ca.* 5 bar for 50 m head, such as at Laodicea or with *ca.* 19 bar for almost 200 m head, as at Pergamum—a very high pressure indeed. According to Torricelli's Law, $v = \sqrt{2 * g * h}$, the resulting flow velocities through the orifice would have been *ca.* 31 m/s (112 km/h) at Laodicea and *ca.* 62 m/s (224 km/h) at Pergamum. It was, therefore, preferable to drain an inverted siphon "top to bottom", opening holes higher up in the line, where pressure was lower, to allow gradual drainage of the water without generating the high flow velocities that would have occurred if drains were located only at the bottom. Sometimes it may not have been necessary to drain the entire inverted siphon because the place that required repair or maintenance was located higher up. In such cases it would have been possible to open a hole just below the damaged section and leave the rest of the inverted siphon filled with water—a good option, as the filling of an empty pipeline was always fraught with risk due to the momentum of the inflowing water. The holes were drilled into the top of the pipeline because water escaping through holes in the side of a pipe would generate a significant reaction force on the pipe acting in the opposite direction of the outflowing water. For a head of *ca.* 50 m and an orifice with 0.1 m diameter in the side wall, that force would be:

$$F = 5 * 10^5 \frac{N}{m^2} * \frac{\pi}{4} * (0.1m)^2 = 3.9kN$$

or roughly 400 kg pulling sideways on the pipe for only one hole. Hence, it was best to locate those drain holes in the top surface of such pipelines so that the reaction force could be countered by the foundation or substructure of the pipeline. Stenton and Coulton (1986: 50) continue: “For drain-holes in the top would leave the long, virtually horizontal stretch of the Aspendos pipeline still full of water.” This is true. Once the pipeline was empty with the exception of the bottommost stretch and the static pressure was correspondingly lower, holes in the side walls were opened to drain the last bit of water from such horizontal stretches. Such holes in the side of the pipeline were found at both Laodicea (Şimşek and Büyükkolancı 2006: 145, n. 22) and Patara (Fahlbusch 1989: 231, 235). Depending on their position and orientation within the individual pipelines, these holes had, therefore, different functions. As I have shown above, they served as air vents to allow air to escape or enter the pipe during filling and draining. At lower elevations in the inverted siphon they served as drain holes, at intermediate elevations as both air vents and drain holes, depending on the height of the water level within. They could also have been points to which branch-off lines were connected, especially if the hole was shaped such that a pipe could fit in sideways (*cf.* Fig 16-1). For pipe segments that are not *in situ* the function of lateral holes cannot be determined.

Figure 16.1: Pipe Hole at Methymna

Some of these holes overlap two adjacent pipe segments, indicating that the pipeline was assembled from prefabricated segments, which were then perforated *in situ* as the location within the line demanded. Once the holes had served their purpose, whether as vents or drains or both, the holes could be securely closed with bungs that were mortared into place. The pipelines at Laodicea ad Lycum and at Patara have evidence of dowel holes and lead seals (Fahlbusch 1989: 244, Fig. 12; Şimşek and Büyükkolancı 2006: 141). This would also explain the small size of these holes, too small for an adult hand to fit through. The holes did not need to be large, because only air or water had to pass through them. The holes were generally tapered, with the narrow end pointing towards the centre line of the pipe (Weber 1898: 6, 8). This funnel shape aided the fitting and securing of the bung, making sure that it could not slip into the pipe and block it. It would have been pure genius on the part of the designers if by their shape the holes produced a sound as the air whistled through them, giving to those in charge an acoustic signal of what stage the filling process currently had reached. This would have allowed engineers at the header tank to vary the flow of water without any delay for flag or voice signals. Musical sounds were a frequent feature of the hydraulic demonstration devices in Philo and Hero. Fake birds were made to whistle, for example, by air that was displaced by water entering a vessel in Hero’s *Pneum.* 14 and 15. Other holes in pipelines were shaped like complex sockets, presumably when they served as connectors for branch-off lines (Stenton and Coulton 1986: 39).

The aqueducts at Pergamum, Smyrna, Alatri, and Segóbriga each could have been built according to the procedure outlined above. Since it was known that air blocks would occur at local high points, air-vent holes were drilled into the sloping segments of the newly laid pipeline before the filling process was started. Fahlbusch (1989: 230) mentions intervals of *ca.* 4 m between holes in the sloping section of the pipeline at Laodicea ad Lycum. As soon as the rising water became visible through each individual hole, starting with the bottommost one, tight-fitting bungs were placed in a prepared mortar bed in the holes and securely lashed in place. A point that is usually forgotten is the necessity to provide for air entry into the pipeline when the aqueduct was drained for maintenance and repair. Everybody who has poured liquid from an upended tetra pack knows that the flow is much ameliorated by poking a hole in the opposite end that allows air to fill the space vacated by the liquid. So, in draining the line, the process was sped up by opening the lateral holes and allowing air to enter the pipe. When the pipeline needed to be drained—an event that may have occurred as often as once every year in winter to prevent freezing water from bursting the pipes, the bungs were removed, and the water could flow out from the pipeline quickly and easily. The average temperature in January at Alatri is 3.4°C and 2°C at Lyon. It is hard to estimate to what extent freezing water was a problem for these ancient pipelines. Hodge (1992: 116, 320) mentions the need of burying pipes 1 m deep underground at Strasbourg and in Britain. More research is necessary along the lines of Rathmayr's (2000) work on the response of people in antiquity to cold climate conditions.

16.1 Population Estimates from Water Supply

The calculations of the flow rates of the inverted siphons allow estimates about population size of the ancient cities. Fahlbusch (1982: 9) assumes for the city of Pergamum an average water requirement of 8-12 liters per day per *capita*, more in summer than in winter. Simply dividing the total amount of water supplied by the aqueducts to the city by that daily requirement would yield impossibly high numbers for the population of the ancient cities. The numbers are necessarily skewed because water was running constantly through the aqueducts, and not just on demand. Moreover, water was used for public purposes as well as for private. Frontinus' categories for water supplied *nomine Caesaris*, *privatis*, and *usibus publicis* provide a reasonably good basis for a population estimate, at least for the Roman period (Fron. *Aq.* 78-86). The amount of water available at the Roman *lacus*, public basins where people could draw water, was, according to Frontinus, *ca.* 10% of the total water available from all nine aqueducts active at the time. For a theoretical population of one million for the city of Rome, these numbers translate to *ca.* 39 liters/day per *capita* that would have been available from 10%

of the total flow rate of the aqueducts (Blackman and Hodge 2001: 125). Transferring this number to cities in other regions at different time periods is fraught with problems because the urban water distribution system in Hellenistic Smyrna was certainly different from that in imperial Rome, and the arid conditions of eastern Iberia would have made people more parsimonious with their water than the temperate climate at Lugdunum. The following theoretical population sizes can be derived by dividing by 10 the flow rate of the aqueduct in question and assuming 39 liters/day per *capita*. The numbers are rounded to the nearest hundred to avoid giving an air of precision that is at present impossible to achieve. It is, furthermore, necessary to remember that Pergamum, Smyrna, and Lugdunum were supplied by more than one aqueduct:

	Flow Rate	Theoretical Number of People Supplied by One Aqueduct
Aspendos	65 liters/s = 5,616 m^3/day	14,400
Yzeron	78-126 liters/s = 6,739-10,886 m^3/day	17,300-27,900
Madradağ	40-45 liters/s = 3,456-3,888 m^3/day	8,900-10,000
Alatri	1.1-3.1 liters/s = 95-268 m^3/day	200-700
Karapınar	15 liters/s = 1,296 m^3/day	3,300
Segóbriga	5.5 liters/s = 475 m^3/day	1,200

Table 16-1: Estimated Population Size

The amount of water delivered by the Madradağ aqueduct accounted for *ca.* half of the total amount available to Hellenistic Pergamum from the Attalos, Demophon, and Madradağ aqueducts (Garbrecht 1987a: 22-4). Hence, a total population size of 18,000-20,000 appears reasonable, which is slightly less than the number of 20,000-40,000 that is generally assumed for Hellenistic Pergamum (Fahlbusch 1982: 9). The Yzeron aqueduct supplied *ca.* 16% of the total water to Lugdunum (Burdy 2002a: 173). The total population, therefore, may have been as high as 103,000-167,000. Burdy (1991a: 7) speculates that the number may have been "des dizaines de milliers d'habitants" when Lugdunum became capital of the Three Gauls. An estimate for Smyrna must be based entirely on conjecture, as no information is available about either the chronological order of the construction of the six aqueducts or the flow rates of the aqueducts other than the Karapınar. Assuming, however, a similar situation as at Pergamum, *i.e.* that the Karapınar aqueduct supplied about half the water available at the time of its construction, yields a population size of *ca.* 6,600, significantly lower than that of Pergamum.

It is instructive to relate the population numbers, derived from the available water, to the surface area of the cities in question:

	Population Based on Water Supply	Inhabited Area	Population Density *ca.* 1/ ha
Aspendos	14,400	24 ha (Kessener and Piras 1997: 160)	600
Lugdunum	103,000-167,000	*ca.* 150 ha (?) (Burdy 2002a: 18)	690-1,100
Pergamum	18,000-20,000	90 ha (Garbrecht 1987a: 18)	200
Alatri	200-700	*ca.* 3 ha (?) based on the 600-m-long circuit wall (Salmon 1976: 36)	67-230
Smyrna	6,600	*ca.* 25 ha (?) based on a walled circumference of 1,730 m (Bürchner 1955b: 752)	260
Segóbriga	1,200	10.5 ha (Abascal, Almagro-Gorbea *et al.* 2005: 8)	110
Rome (for comparison)	1,000,000 (conventional estimate)	1,300 ha based on Aurelian Walls (Blackman and Hodge 2001: 122)	770

Table 16-2: Estimated Population Density

The following conspicuous patterns appear: the Hellenistic cities of Pergamum and Smyrna have a population density of 200 and 260 inhabitants per hectare. These numbers are roughly consistent with Cahill (2002: 38), who quotes a minimum population density of *ca.* 150 inhabitants per hectare for Olynthus before the *anoikismos* of 432 B.C. and a tripling of the total population in the *anoikismos* with a the construction of the houses on the North Hill, leading perhaps to a doubling of the population density to *ca.* 300 inhabitants per hectare (Cahill 2002: 41). The pipelines at Pergamum and Smyrna are located in western Asia Minor, were built in the Hellenistic period, and run across two (Pergamum) and three (Smyrna) natural intermediate high points. The difference between the two is the choice in building material (lead in Pergamum, terracotta and stone in Smyrna), which may have been a question of cost based on the availability of the respective materials or a question of expertise on the part of the local construction crews.

The republican Roman aqueduct at Alatri is an outlier in this group of aqueducts. The population density estimates resulting from the water supply pattern are 67 (after Bassel 1881) to 230 (after Lewis 1999) inhabitants per hectare. Since the flow rate of water in a pipeline is based only on the geometry of the pipe, the logical conclusion is that Bassel's reconstruction of the pipeline geometry is incorrect. Lewis' reconstruction gives 230 inhabitants per hectare, a population density in the range of other 1st-2nd c. B.C. cities in similar hilltop locations, such as Pergamum (*ca.* 200) or Smyrna (*ca* . 260). In proportion, the numbers for Alatri match those for Pergamum and Smyrna. In absolute terms, however, the numbers for Alatri are very small. It seems hardly worthwhile to build an aqueduct at large expense for the benefit of only 200-700 people. The Alatri aqueduct requires a reevaluation through a new site survey. The relatively good correspondence of the numbers for population density demonstrates how an examination of the water supply system can aid in the investigation of demographic patterns.

The similarity of the values for Pergamum, Smyrna, and Alatri, along with the similar physical layout and chronological proximity, appears to confirm Lewis' assertion that the three pipelines are related. I contend, however, that this similarity is an artefact of similar topography. Cities in the Hellenistic and Republican Roman periods were built in hilltop locations. Due to demographic pressure and for reasons of prestige, they needed to be supplied with water. Experience with frequent tectonic activity and the similar topography dictated that the pipeline lead straight across hills that lay between source and city. In short, the three systems are so similar because the conditions to which they responded were similar, too. The problem dictated a solution to which there was no alternative.

According to these calculations, the imperial Roman cities of Aspendos and Lugdunum have population densities of 600 and more inhabitants per hectare. This number is in agreement with the population density of the city of Rome. The population density of Segóbriga (110 inhabitants per hectare) is significantly lower. The reason may be the differential cultural background of the Celtiberian city, which traditionally tended to be a more rural society. Furthermore, the water supply of Segóbriga was supplemented by a system of cisterns. Finally, the water yield of the *qanat* at Fuente de la Mar was evidently not very high to begin with, which is why it had to be augmented by the Fuente de las Zarzas. The hydrology in eastern Spain apparently did not yield more water, so that the value of 39 liters per *capita* may be too high an estimate, given the geophysical conditions in the region. The annual precipitation at the site of Segóbriga today is, with an average of *ca.* 430-460 mm roughly 40-60% less than at the other sites in question.

The advantages of pipelines over free-surface channels have been mentioned earlier. Pipelines are easily concealed, more independent of topography, and their segments could be manufactured off site by methods and from materials that were well known and easily controlled. Pipelines have two significant disadvantages: calcium carbonate deposits from hard water decreased the pipe cross-section at a rate of approximately 2 mm per year, depending on the hardness of the water (Hodge 1992: 227-32). This was a problem for channels, too. For a pipe with an internal diameter of 0.1 m a constriction growing at this rate reduces the cross-sectional area (and hence the flow rate) by 4% per year. Due to the limited size of the pipes and the inaccessibility of the interior surface, this deposit could not be removed by mechanical means. It has been suggested that chemical means for the removal of these deposits existed (Fahlbusch 1991), but this theory is highly doubtful (Humphrey 1992). Roman free-surface flow aqueducts were generally over-dimensioned in order to allow access for maintenance personnel to the line. Mechanical removal of calcium carbonate deposits in such channels was tedious manual work, but it was possible.

The second disadvantage is the limitation of the flow rate by the geometry of the pipeline. The vertical distance between the water levels in header and receiving tank along with the pipe diameter and length are the determining factors for the flow rate. The flow rate cannot be increased beyond the maximum set by these parameters, unless additional pipes are added. An over-dimensioned open channel aqueduct is more flexible than a pipeline regarding the amount of water that it can convey. The ceiling of the channel cover is the limit. An open channel aqueduct can accommodate annual variations in the yield of a spring more easily than a pipeline.

16.2 Literature

The examples above show that ancient pipelines were not standardized. Each pipeline had unique features. Water demand, topography, availability of building material, and financial resources determined the chosen solution. The expectation to find a literary description that comprehensively fits all types of inverted siphons is overly optimistic, especially considering the very limited number of ancient sources that have survived. Even modern technical texts in a familiar language are sometimes difficult to understand; hence the success of the "Dummies" series of manuals. Attempts to understand technical literature from Greek and Roman antiquity pose the challenge of reading texts in a foreign language that explain their subject matter from a point of view that is fundamentally different from the modern understanding of science and technology. Moreover, the authors whose technical works survive today, Vitruvius (1st c. B.C.), Frontinus (1st-2nd c. A.D.), Pliny the Elder (1st c. A.D.), Seneca (1st c. A.D.), Hero (1st c. A.D.?), were socially, chronologically, and spatially remote from those people who were in charge of the design and construction of the inverted siphons. Except perhaps for Hero, none of these authors wrote for an audience of practitioners but rather for their social peers and superiors. Vitruvius was, of course, an architect, familiar with the practical execution of building projects. But his only surviving text, the *De architectura*, was written specifically as a sweeping survey for the instruction of Octavian on matters pertaining to architecture, and not for practical use.

> Conscripsi praescriptiones terminatas ut eas adtendens et ante facta et futura qualia sint opera, per te posses nota habere. Namque his voluminibus aperui omnes disciplinae rationes. (Vitr. 1. *praefatio*)

> I have written down well-defined instructions, so that by referring to them you may have an understanding of works already completed and works in planning. For in these books I have explained all principles of the discipline.

From a modern point of view it is interesting to investigate to what extent the designers understood what they were doing, in particular how they related water requirement to aqueduct size on a quantitative level, and if they understood the behaviour of water in a pipe on a qualitative level. The surviving technical texts from antiquity do not deal with these practical aspects of aqueduct construction and maintenance because either the authors were unfamiliar with such details or their target audience was not interested in them. Ironically we do not know ourselves exactly how water behaves in a gravity-flow pipeline, because modern engineers have sufficient energy available to transport liquids through a pipeline under almost any condition. Testament to our ignorance is the ongoing discussion about the origin, presence or absence, and effect of air in a pipeline. The presence of air downstream from an intermediate high point can now be accepted as an established fact, confirmed by experiment (Nikolic 2003), CFD simulation, and literature (Jordan 1984; Kottmann 1984a). The air bubble gets trapped during the filling process of the pipe. As shown in Chapter 3, some of Hero's automata make use of just this effect, *i.e.* air being pressed upwards by a rising water surface.

Archimedes, too, knew about the layering of fluids of different densities (Garbrecht 1987b: 15). It is clear that practitioners in antiquity were familiar with this effect. The Yzeron aqueduct, for example, was affected by an air block, but the designers dealt with it by building the tower at Craponne.

A quantification of the problem, such as determining the size of the air bubble, is not vital to its solution. The approach to aqueduct construction, at least during the Roman period, was intuitive and based on experience. The aqueducts of the city of Rome were built without any orderly long-term concept and planning. When more water was necessary and sufficient funding was available, a new aqueduct was built (Evans 1994: 136). Channel size did not matter either, because the measure of all things was the human body that needed access to the aqueducts for maintenance. The notion of volume flow rate was understood conceptually, but it was not expressed mathematically, nor did it form a basis for planning and control of the water supply (Garbrecht 1987b: 20). The futile modern attempts at determining the equivalent value of Frontinus' *quinaria* show that a translation of that measure into, say, liters per second is not possible (Hodge 1984; Bruun 2004). Such a conclusion is surprising, since Hero in *Dioptra* 31 clearly relates water discharge to flow velocity and cross-sectional area of the conduit. Furthermore, the description (Vitr. 9.8) and existence of water clocks in antiquity, *e.g.* the Tower of the Winds in Athens, show an understanding of the relation between water flow and time.

The ancient authors and their surviving texts, however, were not concerned with the practical execution of their subject matter. The practical aspect was left to field experts, perhaps from the army, perhaps civilian craftsmen. An expert is an expert only as long as he maintains a monopoly on the set of information that makes him indispensable.

It is, therefore, conceivable that technical information was jealously guarded and passed on only from master to apprentice, either orally or by means of manuals with very limited circulation (Rouse and Ince 1963). It is no surprise that Roman authors of senatorial rank, such as Frontinus or Pliny, had no access, and perhaps no interest, in such manuals.

The understanding of hydraulic phenomena in antiquity was largely based on speculation and philosophy. This qualitative aspect is emphasized in literature by the parallels evident in the vocabulary used for functions of the human body, in particular digestion and blood circulation. The CFD-simulation shows significant turbulence in the interface between water and air in the pipe. Snapshots from the CFD-experiment show air rushing in and out of the mouths of the pipeline, sucked and driven by the moving water. These phenomena were, no doubt, accompanied by significant noise, reminiscent of flatulence. The urban distribution network of pipelines has some obvious similarities with the network of veins and arteries in the human body. Aristotle draws this comparison:

> Ἔοικε δ’ ὥσπερ ἔν τε τοῖς κήποις αἱ ὑδραγωγίαι κατασκευάζονται ἀπὸ μιᾶς ἀρχῆς καὶ πηγῆς εἰς πολλοὺς ὀχετοὺς καὶ ἄλλους ἀεὶ πρὸς τὸ πάντῃ μεταδιδόναι… (Arist. *PA* 668a)

> [The system of blood vessels in the human body] is just like the water channels that are prepared in gardens. From one source or spring they branch out into many channels and then into others, throughout the garden… (trans. Oleson)

Natural philosophy in antiquity was not divided into the modern multiplicity of disciplines. Parallels between disparate, but similar physical or biological phenomena would have been very obvious to an ancient philosopher. Ortloff and Kassinos (2003) observed oscillations in their simulation of the pipeline at Aspendos that invite a comparison with respiration or a heartbeat.

16.3 Conclusion

Initially a two-pronged approach to the application of CFD to the research of ancient pipelines was intended. On the one hand, a proof-of-concept experiment was supposed to show that the chosen research method of computer simulations is a viable technique to demonstrate the complexity of air-water interaction in water pipelines. On the other hand, the experiments were supposed to provide reliable numerical results for the main flow properties of water in a number of selected ancient pipelines. Delays and difficulties, as are normal in any experimental project, made it necessary to branch out to include a large segment with conventional calculations of flow velocity, flow rate, and size of air bubbles. Moreover, a significant portion of the project investigates literary evidence and compares terminology from relevant Roman technical literature with Greek medical texts.

Despite the unexpected modifications that were necessary, the project was a great success. The following original results summarize the successful outcome: the project identifies and describes seven ancient long-distance water pipelines with one or more intermediate high points as common features: Karapınar (Smyrna), Madradağ (Pergamum), Methymna, Alatri, Segóbriga, Yzeron (Lugdunum), and Aspendos. The catalogue of systems with this feature is relevant for two reasons: at Methymna, Yzeron, and Aspendos the high points are man-made and were included in the line at considerable expense in labour and material. The reason for the inclusion of these artificial features at

Aspendos had not been explained satisfactorily, and only a direct comparison with a larger number of similar pipelines can serve to verify previous theories. An intermediate high point in a pipeline leads, during the filling process, to the formation of an air bubble, which has the potential to render the pipeline useless because in gravity-flow systems without additional supply of energy such a bubble reduces the available head, *i.e.* the vertical distance between the water surfaces in header and receiving tank by the vertical extent of the bubble. If the bubble is larger top to bottom than the available head, then the water is unable to travel through to the receiving end because no pressure differential is available to supply sufficient energy.

The aqueduct descriptions in this work include the physical properties of the pipelines and place them in the natural and cultural context of their sites. Prior work on these aqueducts described only individual pipelines in isolation or compared, at most, pipelines from three different sites. This dissertation for the first time assembles information pertaining to seven such systems and presents this information in a standardized catalogue, supplemented with tables, diagrams, and images that illustrate the main points. The collected data serve to determine the basic flow properties and the size of occurring air bubbles. For the aqueducts at Pergamum, Yzeron, and Aspendos, previous values for flow rate and flow velocity are available for comparison. The new results are similar to those from the previously available calculations. The calculations for Smyrna, Alatri, and Segóbriga are original. Values for Methymna cannot be determined, because the information about the pipeline is insufficient. A survey of the remains of this interesting aqueduct is necessary as a follow-up project. This project makes the numerical results for all pipelines directly comparable because it utilizes the same equations and the same method for generating and presenting the results for each system. Furthermore, I give details about all assumptions that form the basis for the calculations, such as the roughness coefficients of the pipes; not all previous publications have done so.

In contrast to previous publications, I clearly explain the reason for the occurrence of air bubbles in the pipeline. The problem is not air entrainment at the header tank, nor is it air that comes out of solution from the water. The problem is that air is trapped downstream from the intermediate high points by water columns converging from both sides until the air is compressed to a maximum by the water. Hodge (1983: 206), Tölle-Kastenbein (1991: 29), and Kessener (2003: 154) mention this phenomenon, but do not explain or understand the precise mechanism behind it. The calculations of the size of the air bubbles occurring in the pipelines are original and correspond with those in Jordan (1984), a handbook intended for engineers working in remote areas of developing countries under conditions similar to those encountered by ancient engineers. The calculation of the size of air bubbles shows that the available head was completely sufficient to overcome the air blocks at Pergamum and Segóbriga. The available head was barely sufficient to transport the water to the receiving end at Smyrna and Alatri. At Yzeron the available head was not sufficient to overcome the air block, which is why the tower, equipped with an open basin, was necessary to provide an outlet for the accumulating air. Is it conceivable, therefore, that the lateral holes that Weber saw in the pipe segments at Smyrna were drilled for draining the resulting air bubbles, and that they were closed with tight-fitting bungs as soon as the rising water became visible or audible. No pipe segments with lateral holes survive from the lead pipeline at Alatri, but a scenario similar to that at Smyrna is possible. An alternative possibility is that the positions of header or receiving tanks, based on conjecture at Smyrna, Alatri, and Segóbriga, were different than is currently assumed. The available head would change with a different position of these tanks, and the greater the vertical distance between the two extreme ends, the less problematic would have been the occurrence of an air block. With these numbers in hand it is possible to revisit the individual sites and reexamine the positions of the starting and end points of the pipelines.

Tölle-Kastenbein (1991: 29) suggests rightly that these holes served to vent air from the pipelines, but proposes a close link with the Vitruvian term *vis spiritus* and erroneously equates the holes with *colluviaria*. My suggestion is that these lateral holes in the pipes served three purposes, depending on their location in the inverted siphon. They were used to vent air bubbles occurring at the downstream side of intermediate high points, they served as drain holes for the water when the inverted siphon was fully or partially emptied, and they served to admit air into the pipeline when the water was drained from the inverted siphon.

The pipelines at Smyrna, Pergamum, Alatri, and Segóbriga were built across intermediate hills in order to cross the topographic contour lines at right angles, so that there would be no need for lateral anchoring against erosion—an important aspect in regions that experience earthquakes or torrential rainfall. The pipeline at Yzeron was built in an almost straight line that required the least possible amount of lead. As a result, it had to cross an intermediate high point of modest prominence that required the construction of a tower for venting trapped air. The purpose of the towers at Aspendos is still unknown. The unsatisfactory, awkward explanation that they were built to eliminate lateral forces caused by static pressure is a possibility. The towers do, indeed, eliminate these forces. It is not known whether this effect is what was actually desired by the ancient designers. Kessener's frequent assertion that the towers eliminated the effects of water hammer, potentially destructive pressure waves caused by sudden changes in flow velocity, is erroneous. The form of the towers is not suitable to alleviate water hammer. Modern devices that alleviate water hammer do not consist of bent portions of pipe but are located in straight sections with a branch-off at a right angle.

16.4 Ancient Literature and CFD

Some misconceptions about the behavior of water in ancient pipelines were caused by imprecise translations of key terms from ancient technical texts, Vitruvius in particular. The terms *libramentum*, *venter*, and *spiritus* have been translated in the past as "gradient", "bridge", and "air". In the context of inverted siphons it is more appropriate to translate them as "level", "inverted siphon", and "pressure". Further comparison of Roman technical literature with Greek medical texts shows much promise for future research since technical phenomena were frequently compared to bodily functions, more precisely digestion and blood flow. A satisfactory translation of the puzzling term *colluviaria* is still not evident. Investigation of the term *vis spiritus*, however, has shown that the function of *colluviaria* was not to relax the "force of the air" but rather the "force of pressure". It is conceivable that Vitruvius derived *colluviaria* from the Greek συλλύω, "to help in loosing".

I suggest the following possibility: The reason why nobody has found clear archaeological evidence of *colluviaria* in ancient aqueducts is because, misled by Vitruvius, we have been looking in the wrong places. If we accept Vitruvius' assertion that the function of *colluviaria* was pressure reduction (*per quae vis spiritus relaxetur*, Vitr. 8.6.6), then plenty of examples of such devices survive in the archaeological record. They are the water towers in Pompeii (Larsen 1982), the *suterazı* in Constantinople (Andréossy 1828; Forchheimer and Strzygowski 1893b), and the mediaeval water tower in Goslar (Flachsbart 1928). These features, however, were built not into long-distance pipelines but into the urban distribution systems as pressure reducers. Their function was crucial for protecting the integrity of taps or private distribution boxes, made of lead or bronze, used by private consumers at the end of the line (Peleg 2000: 243; Jansen 2001). These taps or boxes may not have been able to withstand pressures resulting from a water column that reached all the way up to the main *castellum*, typically located at the highest point of the city. With these towers the maximum pressure the closed taps had to hold was reduced to the static pressure generated by the vertical water column of the tower, *e.g.* 0.6 bar for a tower 6 m high instead of 2 bar for an elevation difference of, say, 20 m between the tap and the primary *castellum*.

The CFD-simulation was successful in reproducing in 2D a physical experiment with a rubber hose that was used to simulate a small-scale inverted siphon with intermediate high point (Nikolic 2003). The simulation of large-scale aqueducts at 1:1 was very difficult due to the large size of the computational domain. Time constraints and limitations with respect to computing resources cut short this portion of the experiment. As a proof-of-concept experiment, however, these tests were a success. The CFD-simulation of the filling process of an ancient long-distance pipeline has never been attempted before. The problems encountered in this project are steps along a steep learning curve. The method is viable and, given sufficient time and computer resources, has the potential for great results in the future.

Overall, the project was brought to a successful conclusion with interesting and relevant results on the archaeological, philological, and technical side, as well as promising routes for future research.

16.5 Future Research

16.5.1 Archaeological

All relevant information about the physical properties of the pipelines in this catalogue must be brought to the excellent standard of the system descriptions of Pergamum (Garbrecht 1978), Yzeron (Burdy 1991a), and Aspendos (Kessener 2000a).

Survey of the inverted siphon at Smyrna: The city of Izmir has grown significantly since Weber's work in the late 19th century. It is highly unlikely that any traces of the Karapınar aqueduct have survived the modern urban expansion. It is, nonetheless, possible and necessary to generate a new topographic map of the city that includes the positions of all characteristic points of the inverted siphon that were identified by Weber.

Survey of the inverted siphon at Methymna: Koldewey's topographic map of Methymna and surroundings needs to be corrected and updated. The water tower must be thoroughly described, measured, and interpreted. Furthermore, it is necessary to record by GPS the number and positions of the scattered preserved stone pipe fragments and to analyze their distribution with GIS software in order to establish the likely route that the aqueduct took. This work must be done quickly before the remaining pipe fragments disappear. The positions of the spring and of the receiving end of the aqueduct must be identified.

Survey of the inverted siphon at Alatri: It is necessary to generate a topographic map of the area north of Alatri and to identify the route of the inverted siphon. The relevant work on the aqueduct was conducted more than 100 years ago and requires an update.

Survey of the inverted siphon at Segóbriga: The route of the aqueduct requires confirmation. It is necessary to correct the scale of the topographic map from 1976. The area south of the modern town of Saelices has experienced significant modifications due to the recent construction of the highway between Madrid and Valencia. It is necessary to evaluate the damage done to the remains of the aqueduct.

Relevant information about sites that were supplied with water by means of inverted siphons without intermediate high points must be collected from previous work. A good starting point is the list by Hodge (1992: 428, n.43). The data must be assembled in a standardized catalogue. The unclear layout of pipelines such as those at Termini Imerese (Belvedere 1986) and at Lincoln (Thompson 1954) require clarification and update. It is probable that more inverted siphons await discovery. In many cases the material evidence may not have been preserved. It is, therefore, necessary to draw inferences from the topography around these sites, such as the hydrological catchment area, which allows deductions regarding the existence of long-distance water pipelines. Information from ancient authors, such as Strabo, may provide more clues about so far undetected inverted siphons.

16.5.2 Technical

Once all information about pipeline material, layout, and size is available, it is possible to calculate the main flow properties, such as flow velocity, flow rate, and maximum water pressure, following the model of the six pipelines presented in this work. These data must be added to the catalogue established in this project, where they will be directly comparable with one another and easily available as raw data for further research and interpretation, *e.g.* in relation to the size of urban populations.

The CFD-simulations require much modification. Since the size of the computational domain was a big problem, it is necessary to reduce its size. It is possible to break up the length of the aqueduct into more manageable portions. A break-up of the computational domain means, however, a loss of information about phenomena occurring simultaneously at opposite ends of the system, such as the onset of oscillations or air flow at the receiving end of the inverted siphon. Another possibility, which was successful in this project, is the scaling-down of the model, accepting that the numerical results will be only qualitatively, not quantitatively comparable to real-life results. The same problem would occur in a physical scale model in which the properties of water and air cannot be reduced to the same scale as the geometry of the pipeline. It must be emphasized, however, that the problems with the CFD-simulation were not caused by the software or the methodology. They were largely the consequence of a lengthy learning process, hardware problems, and maintenance schedules, basically a mix of the complexity of the experimental setup, unfortunate timing, and bad luck. The simulations will continue in follow-up research. Based on the experience of this dissertation it appears advisable to outsource this portion of the project to an engineering researcher who can commit his attention exclusively to the solution of occurring problems and who is capable of writing original code that may improve the performance of the experiment. Other CFD-packages, such as Flow-3D, can be tested for better suitability to the problem. Ortloff (1998) has shown that smaller hydraulic features can be simulated with Flow-3D without much difficulty. Small portions of a long-distance pipeline can be investigated in isolation to examine to effect of an air bubble escaping through a lateral leak in the pipe wall, answering the question whether such a phenomenon will cause water hammer or not. This simulation was not attempted during this project due to the particular complexity of the initial geometric model. More experience in the generation of geometry and computational grid using either GAMBIT or ICEM CFD is necessary for the successful running of such a simulation.

A lateral expansion of the project is conceivable to include an expert on water chemistry who can investigate the effects of sinter formation on the pipe walls depending on the content of calcium carbonate in the water and on seasonal variations in water temperature. Only little previous work on the topic exists (Schmitz 1978; Grewe and Blackman 2001). Such an investigation will give valuable insight into the necessity and frequency of regular maintenance and cleaning procedures.

16.5.3 Literary

This project has shown the close relationship between Greek and Latin proto-scientific texts in the context of water supply systems. The results presented here, however, merely scratch the surface of the potential inherent in such a comparison. It is necessary to mine ancient texts, such as the Hippocratic, Aristotelian, and Galenic *corpora* for their descriptions of blood circulation and of the digestive system, as these correspond very closely to the function of pipelines where matter enters a system, moves through it, and is expelled at the opposite end through a force that is invisible to the eye. Comparisons with Latin texts by Celsus, Seneca, and Pliny the Elder, will be instructive. An investigation of Seneca and Pliny must focus on extracting all passages related to the transport of water, as was begun for Pliny by Minonzio (2004), but also on passages relating to the above mentioned bodily functions. The Greek and Latin medical texts will provide information about disruptions and ailments of the circulatory and digestive systems that can be, as this project has shown, sometimes directly transferred to problems in a water pipeline. Signal words, *e.*g. *spiritus* or πνεῦμα, have proven to be fruitful starting points for investigation. Recent and ongoing work focusing on the structure and characteristics of Roman texts and their perceived poverty in terminology compared with ancient Greek, *e.g.* Fögen (2000), can serve as supplemental material in the context of technical terms, such as *colluviaria*, that are notoriously difficult to translate.

Bibliography

Abascal, J. M., M. Almagro-Gorbea, and R. Cebrián. 2005. *Segóbriga*. Madrid: Real Academia de la Historia.

Abascal, J. M., M. Almagro Gorbea, and R. Cebrián. 2006. "Segobriga: *caput Celtiberiae* and Latin *municipium*," in A. Abad Casal, S. Keay, and S. Ramallo Asensio (edd.), *Early Roman Towns in Hispania Tarraconensis*. JRA Suppl. 62. 184-96. Portsmouth, RI: Journal of Roman Archaeology.

Aicher, P. J. 1995. *Guide to the Aqueducts of Ancient Rome*. Wauconda: Bolchazy-Carducci Publishers, Inc.

Akurgal, E. 1976. "Smyrna," in R. Stillwell, W. L. MacDonald, and M. H. McAllister (edd.), *PECS*. 847-48. Princeton, NJ: Princeton University Press.

———. 1990. *Ancient Civilizations and Ruins of Turkey*, 7th ed. Istanbul: Net Turistik Yayinlar A. S.

Almagro-Gorbea, M. 1989. "La romanización de Segóbriga." Paper read at *Conquista romana y modos de intervención en la organización urbana y territorial. Primer congreso histórico-arqueológico hispano-italiano*, 26-29 October, at Elche.

Almagro Basch, M. 1976. "El acueducto romano de Segóbriga." *Revista de Archivos, Bibliotecas y Museos* 79: 875-902.

———. 1978. "Datos cronológicos para fechar el acueducto de Segóbriga." *Revista de Archivos, Bibliotecas y Museos* 81: 155-67.

Almagro Gorbea, M. 1987. "La urbanización augústea de Segóbriga." Paper read at *Stadtbild und Ideologie: Die Monumentalisierung hispanischer Städte zwischen Republik und Kaiserzeit*, 19-23 October, at Madrid.

Almagro Gorbea, M. and J. M. Abascal Palazón. 1999. *Segóbriga y su conjunto arqueológico*. Madrid: Real Academia de la Historia.

Amedick, R. 1998. "Ein Vergnügen für Augen und Ohren: Wasserspiele und klingende Kunstwerke in der Antike." *Antike Welt* 29: 497-507.

Andréossy, A. F., comte d'. 1828. *Constantinople et le Bosphore de Thrace pendant les années 1812, 1813, et 1814 et pendant l'année 1826 : avec un atlas composé de six planches gravées, et de quatre paysages lithographiés*. Paris: T. Barrois et B. Duprat (A. Belin).

Ashby, T. 1935. *The Aqueducts of Ancient Rome*. Oxford: Clarendon Press.

Avallone, E. A. and T. Baumeister (edd.) 1996. *Marks' Standard Handbook for Mechanical Engineers*. 10th ed. New York: McGraw-Hill.

Baines, W. D. and D. L. Wilkinson. 1986. "Motion of Large Air Bubbles in Ducts of Moderate Slope." *Journal of Hydraulic Research* 25 (3): 157-70.

Balsamo, E. 1958. "L'acquedotto Cornelio di Termini Imerese." Paper read at *Rotary Club di Termini Imerese*, November 26th, at Termini Imerese.

Bammer, A. 1972. "Neue Forschungen am Altar des Artemisions von Ephesos." *Archäologischer Anzeiger*: 714-28.

Bassel, R. 1881a. "Antike Hochdruckwasserleitung des Betilienus in Alatri." *Centralblatt der Bauverwaltung*: 134-35.

———. 1881b. "Antike Hochdruckwasserleitung des Betilienus in Alatri." *Centralblatt der Bauverwaltung*: 121-22.

———. 1882. "Antike Hochdruckwasserleitung des Betilienus in Alatri." *Centralblatt der Bauverwaltung*: 436.

———. 1919. "Die Druckrohrleitung des Betilienus in Alatri." *Zentralblatt der Bauverwaltung*: 8.

Bean, G. E. 1976. "Aspendos," in R. Stillwell, W. L. MacDonald, and M. H. McAllister (edd.), *PECS*. 101-03. Princeton, NJ: Princeton University Press.

Belvedere, O. 1986. *L'acquedotto Cornelio di Termini Imerese*. Rome: L'Erma di Brettschneider.

———. 2000. "The Barratina Siphon in the Acqua Cornelia of Termini Imerese: Archaeological and Technical Problems," in G. C. M. Jansen (ed.) *Cura Aquarum in Sicilia*. 105-08. Leiden: BABesch.

Bestué Cardiel, I. and I. González Tascón. 2006. "Roman Siphons in Spain," in G. Wiplinger (ed.) *Cura Aquarum in Ephesus* Vol. 1. 311-17. Leuven: Peeters.

Biernacka-Lubanska, M. 1998. "Roman Lead Pipe Production Technology." *Novaensia* 10: 31-45.

Blackman, D. and A. T. Hodge. 2001. *Frontinus' Legacy*. Ann Arbor: University of Michigan Press.

Blackman, D. and Y. Peleg. 2001. "Two Sets of Technical Comments on P. Kessener, 'The Aqueduct at Aspendos', JRA 13." *Journal of Roman Archaeology* 14: 411-13.

Blake, M. E. 1968. *Roman Construction in Italy from Tiberius through the Flavians*. New York: Kraus Reprint Corp.

Bruun, C. 2004. "The Impossibility of Reaching an Exact Value for the Roman *Quinaria* Measure," in R. H. Rodgers (ed.) *Frontinus: De aquaeductu urbis romae*. 342-46. Cambridge: Cambridge University Press.

Buchholz, H.-G. 1976. *Methymna: Archäologische Beiträge zur Topographie und Geschichte von Nordlesbos*. Mainz: P. von Zabern.

Bürchner, L. 1955a. "Lesbos," *RE XII, 1*. 2107-33.

———. 1955b. "Smyrna," *RE III A, 1*. 727-65.

Burdy, J. 1987. *L'aqueduc romain du Mont d'Or*. Préinventaire des monuments et richesses artistiques I. Lyon: Conseil Général du Département du Rhône.

———. 1991a. *Lyon: L'aqueduc romain de l'Yzeron*. Préinventaire des monuments et richesses artistiques II. Lyon: Conseil Général du Département du Rhône.

———. 1991b. "Some Directions of Future Research for the Aqueducts of Lugdunum (Lyon)," in A. T. Hodge (ed.) *Future Currents in Aqueduct Studies*. Collected classical papers 2. 29-44. Leeds: Francis Cairns.

———. 1993. *Lyon: L'aqueduc romain de la Brévenne*. Préinventaire des monuments et richesses artistiques III. Lyon: Conseil Général du Département du Rhône.

———. 1996. *Lyon: L'aqueduc romain du Gier*. Préinventaire des monuments et richesses artistiques IV. Lyon: Conseil Général du Département du Rhône.

———. 2002a. *Les aqueducs romains de Lyon*. Lyon: Presses universitaires de Lyon.

———. 2002b. "The Siphon-Bridges of the Gier Roman Aqueduct (Lyons). Inclined Decks and Open Piers," in C. Ohlig, Y. Peleg, and T. Tsuk (edd.), *Cura Aquarum in Israel*. 239-52. Siegburg: Deutsche wasserhistorische Gesellschaft.

Cahill, N. 2002. *Household and City Organization at Olynthus*. New Haven: Yale University Press.

Callebat, L. 1973. *Vitruve, de l'architecture, livre VIII*. Association Guillaume Budé. Paris: Société d'Édition "Les Belles Lettres".

Callebat, L., *et al.* 1984. *De Architectura Concordance*. Vol. 1. Hildesheim: Olms-Weidmann.

Chanson, H. 2000. "Hydraulics of Roman Aqueducts: Steep Chutes, Cascades, and Dropshafts." *American Journal of Archaeology* 104 (1): 47-72.

Chatenet, C. 2003. *Les aqueducs romains de Lyon*. Website. École Centrale de Lyon, last update September 2003. Available http://chappe.ec-lyon.fr/. Access date 12 May 2006.

Çilingiroglu, A., *et al.* 2004. *Ulucak Höyük: Excavations Conducted Between 1995 and 2002*. Ancient Near Eastern Studies Supplement 15. Louvain: Peeters.

Cramer, F. 1955. "Lugudunum," *RE XIII, 2*. 1718-23.

Cuomo, S. 2001. *Ancient Mathematics*. London: Routledge.

Dalley, S. and J. P. Oleson. 2003. "Sennacherib, Archimedes, and the Water Screw: The Context of Invention in the Ancient World." *Technology and Culture* 44 (1): 1-26.

De Kleijn, G. 2001. *The Water Supply of Ancient Rome*. Nijmegen: Gieben.

De Minicis, E. 1980. "Alatri," in I. Belli Barsali (ed.) *Lazio Medievale. 33 abitati delle antiche diocesi di Alatri, Anagni, Ferentino, Veroli*. 1-23. Rome: Multigrafica.

de Montauzan, C. G. 1909. *Les aqueducs antiques de Lyon*. Paris: Ernest Leroux.

Del Chicca, F. (ed.) 2004. *Sextus Julius Frontinus: De aquae ductu urbis Romae*. Rome: Herder.

DeLaine, J. 1996. "'De aquis suis'?: The 'commentarius' of Frontinus," in C. Nicolet (ed.) *Les littératures techniques dans l'Antiquité romaine.* Entretiens sur l'Antiquité classique, 42. 117-45. Vandoeuvres-Genève: Fondation Hardt.

Diels, H. and W. Kranz. 1951. *Die Fragmente der Vorsokratiker: griechisch und deutsch*, 6th ed. Berlin: Weidmann.

Drachmann, A. G. 1948. *Ktesibios, Philon, and Heron: A Study in Ancient Pneumatics*. Vol. 4. Acta Historica Scientiarum Naturalium et Medicinalium. Copenhagen: Munksgaard.

———. 1976. "Ktesibios' Waterclock and Heron's Adjustable Siphon." *Centaurus* 20: 1-10.

Eastop, T. D. and A. M. McKonkey. 1986. *Applied Thermodynamics for Engineering Technologists*, 4th ed. Harlow: Longman Scientific & Technical.

Evans, H. B. 1994. *Water Distribution in Ancient Rome: the Evidence of Frontinus*. Ann Arbor: University of Michigan Press.

Fabio, E. and L. Fassitelli. *Roma: tubi e valvole*. Milan: Petrolieri d'Italia.

Fahlbusch, H. 1982. "Vergleich antiker griechischer und römischer Wasserversorgungsanlagen." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 73.

———. 1987. "Vitruvius and Frontinus: Hydraulics in the Roman Period," in G. Garbrecht (ed.) *Hydraulics and Hydraulic Research*. 23-32. Rotterdam.

———. 1989. "Überlegungen zur möglichen Entsinterung von Druckrohren im verlauf römischer Fernwasserleitungen." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 103: 219-45.

———. 1991. "Maintenance Problems in Ancient Aqueducts," in A. T. Hodge (ed.) *Future Currents in Aqueduct Studies*. Collected classical papers 2. 7-14. Leeds: Francis Cairns.

Fahlbusch, H. and J. Peleg. 1992. "Die Colliviaria Vitruvs - Möglichkeiten der Interpretation." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 117: 105-40.

Falvey, H. T. 1980. *Air-Water Flow in Hydraulic Structures*. Denver: US Department of the Interior.

Feder, L. 1998. *The Handbook of Classical Literature*. New York: Da Capo Press.

Fernandez-Casado, C. 1983. *Inginieria hidraulica romana*. Madrid: Ediciones Turner.

Flachsbart, O. 1928. *Geschichte der Goslarer Wasserwirtschaft*. Dissertation, Technische Hochschule Hannover, Hannover.

Fluent 6.1. Fluent Inc., Lebonon, NH.

Fögen, T. 2000. *Patrii sermonis egestas: Einstellungen lateinischer Autoren zu ihrer Muttersprache*. Beiträge zur Altertumskunde 150. Munich: K. G. Saur.

Forbes, R. J. 1964. *Studies in Ancient Technology*. Vol. 8. Leiden: Brill.

Forchheimer, P. 1923. "Wasserleitungen," *Forschungen in Ephesos* Vol. III. 224-55. Vienna: Österreichische Verlagsgesellschaft Ed. Hölzel & Co., Ges. m. b. H.

Forchheimer, P. and J. Strzygowski. 1893a. *Die Byzantinischen Wasserbehälter von Konstantinopel*. J. Strzygowski (ed.). Byzantinische Denkmäler. Vienna: Gerold & Comp.

———. 1893b. *Die byzantinischen Wasserbehälter von Konstantinopel*. J. Strzygowski (ed.). Byzantinische Denkmäler 2. Vienna: Verlag der Mechitharisten-Congregation in Wien.

Gandenberger, W. 1957. *Über die wirtschaftliche und betriebssichere Gestaltung von Fernwasserleitungen*. Munich: Oldenbourg.

Garbrecht, G. 1978. "Wasserwirtschaftliche Anlagen des antiken Pergamon: die Druckleitung." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 60.

———. 1987a. "Die Wasserversorgung des antiken Pergamon," *Die Wasserversorgung antiker Städte* Vol. 2. 11-48. Mainz: von Zabern.

———. 1987b. "Hydrologic and Hydraulic Concepts in Antiquity," in G. Garbrecht (ed.) *Hydraulics and Hydraulic Research*. 1-22. Rotterdam: A. A. Balkema.

Garbrecht, G. and H. Fahlbusch. 1975. "Wasserwirtschaftliche Anlagen des antiken Pergamon: die Kaikos-Leitung." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 44.

———. 1978. "Wasserwirtschaftliche Anlagen des antiken Pergamon: Umbau und Neubau der Kaikos-Leitung." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 60.

Garbrecht, G. and G. Holtorff. 1973. "Wasserwirtschaftliche Anlagen des antiken Pergamon: die Madradag-Leitung." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 37.

Gasperini, L. 1965. *Aletrium*. Vol. I. Quaderni dell'istituto di storia ed arte del Lazio meridionale. Frosinone: Istituto di Storia ed Arte del Lazio Meridionale.

Gieck, K. and R. Gieck. 1990. *Technical Formulae*. J. Walters (trans.), 7th ed. Germering: Gieck-Verlag.

Gimpel, J. 1976. *The Medieval Machine*. Harmondsworth: Penguin.

Glare, P. G. W. (ed.) 1982. *Oxford Latin Dictionary*. Oxford: Clarendon Press.

Google Earth Plus 4.0.2091 (beta). Google Inc.

Granger, F. S. 1983. *Vitruvius: On Architecture*. 2 vols. Loeb Classical Library. Cambridge, MA: Harvard University Press.

Grewe, K. 1984. "Römische Wasserleitungen in Spanien." *Schriftenreihe der Frontinus-Gesellschaft* 7: 7-48.

Grewe, K. and D. Blackman. 2001. "Excursus on *Calx*," in D. Blackman and A. T. Hodge (edd.), *Frontinus' Legacy*. 109-15. Ann Arbor: University of Michigan Press.

Grewe, K., H. P. M. Kessener, and S. Piras. 1999. "Im Zickzack-Kurs über den Fluss: Die römisch/seldschukische Eurymedon-Brücke von Aspendos (Türkei)." *Antike Welt* 30: 1-12.

Grimal, P. 1945. "Vitruve et la technique des aquéducs." *Révue de philologie* 19: 162-74.

Harmeling, S., M. Stitz, and P. Mesenburg. 1999. "Die Brücke von Aspendos." *Der Vermessungsingenieur* 2: 110-15.

Harris, C. R. S. 1973. *The Heart and the Vascular System in Ancient Greek Medicine, from Alcmaeon to Galen*. Oxford: Clarendon Press.

Hecht, K. 1975. "Die wasserwirtschaftlichen Anlagen des antiken Pergamon: Zwei Aquädukte der Kaikos-Leitung." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 45.

———. 1977. "Wasserwirtschaftliche Anlagen des antiken Pergamon: Zwei weitere Aquädukte der Kaikos-Leitung." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 54.

———. 1983. "Wasserwirtschaftliche Anlagen des antiken Pergamon: Die Aquädukte der Madradag-Kanalleitung sowie der Aquädukte XLII und XLIII der Aksu-Leitung (Feldbuch und Bauaufnahme, Prof. Dr.-Ing. K. Hecht, 1979)." *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 78.

Heinrich, D. and M. Hergt (edd.) 1990. *Atlas zur Ökologie*. Munich: Deutscher Taschenbuch Verlag.

Hill, D. R. 1979. *The Book of Ingenious Devices (Kitāb al-Hiyal) by the Banū (sons of) Mūsā ibn Shākir*. Dordrecht: Reidel.

Hoare, R. 2006. *World Climate*. Website. Buttle and Tuttle Inc., last update 5 January 2006. Available http://www.worldclimate.com/. Access date June 2006.

Hodge, A. T. 1983. "Siphons in Roman Aqueducts." *Papers of the British School at Rome* 51: 174-221.

———. 1984. "How Did Frontinus Measure the Quinaria?" *American Journal of Archaeology* 88 (2): 205-16.

———. 1992. *Roman Aqueducts & Water Supply*. London: Duckworth.

———. 2000a. "Aqueducts," in Ö. Wikander (ed.) *Handbook of Ancient Water Technology*. 39-65. Leiden: Brill.

———. 2000b. "Engineering Works," in Ö. Wikander (ed.) *Handbook of Ancient Water Technology*. 67-94. Leiden: Brill.

———. 2000c. "Qanats," in Ö. Wikander (ed.) *Handbook of Ancient Water Technology*. 35-38. Leiden: Brill.

Hübner, E. 1955. "Ercavica," *RE VI, 1*. 397-98.

Humphrey, J. W. 1992. "Review of 'Future Currents in Aqueduct Studies'." *Classical Views/Echos du monde classique* 36 (2): 244-48.

Humphrey, J. W., J. P. Oleson, and A. N. Sherwood. 1998. *Greek and Roman Technology: A Sourcebook*. New York: Routledge.

Inversin, A. R. 1986. *Micro-Hydropower Sourcebook: A Practical Guide to Design and Implementation in Developing Countries*. Washington DC: NRECA International Foundation.

Jameson, S. 1970. "Aspendos," *RE Supplement XII*. 99-109.

Jansen, G. C. M. 2000. "Urban Water Transport and Distribution," in Ö. Wikander (ed.) *Handbook of Ancient Water Technology*. 103-25. Leiden: Brill.

———. 2001. "Water Pipe Systems in the Houses of Pompeii: Distribution and Use," in A. O. Koloski-Ostrow (ed.) *Water Use and Hydraulics in the Roman City*. 27-40. Dubuque: Kendall/Hunt Publishing Company.

———. 2005. "Water and Water technology in the Pompeian Garden," in S. T. A. M. Mols and E. M. Moormann (edd.), *Omni pede stare: saggi architettonici e circumvesuviani in memoriam Jos de Waele*. Studi della Soprintendenza archeologica di Pompei 9. 277-90. Naples: Electa Napoli and Ministero per i Beni e le Attività Culturali.

Jordan, T. D. 1984. *A Handbook of Gravity-Flow Water Systems*. London: Intermediate Technology Publications.

Ju, A. E. 2007. "Chrysippus on Nature and Soul in Animals." *Classical Quarterly* 57 (1): 97-108.

Kahn, C. H. 2003. "Pythagoras," in S. Hornblower and A. Spawforth (edd.), *OCD*. 1281-2. Oxford: Oxford University Press.

Käppeli, E. 1987. *Strömungslehre und Strömunsgsmaschinen*, 5th ed. Frankfurt a. M.: Harry Deutsch.

Kessener, H. P. M. 2000a. "The Aspendos Aqueduct and its Inverted Siphon." *Journal of Roman Archaeology* 13: 104-32.

———. 2000b. "The Aspendos Aqueduct Research Project (AARP): Field Campaigns 1996 and 1998," in G. C. M. Jansen (ed.) *Cura Aquarum in Sicilia*. 145-54. Leiden: BABesch.

———. 2001. "Vitruvius and the Conveyance of Water." *BABesch* 76: 139-58.

———. 2002a. "Response to the Comments of D. R. Blackman and Y. Peleg (JRA 14, 411-14)." *Journal of Roman Archaeology* 15: 349-51.

———. 2002b. "Vitruvius rehabilitandus est," in C. Ohlig, Y. Peleg, and T. Tsuk (edd.), *Cura Aquarum in Israel*. 187-200. Siegburg: Schriften der deutschen wasserhistorischen Gesellschaft.

———. 2003. "Roman Water Transport: Problems in Operating Pressurized Pipeline Systems," in C. Ohlig (ed.) *Wasserhistorische Forschungen--Schwerpunkt Antike*. 147-60. Siegburg: Deutsche Wasserhistorische Gesellschaft.

Kessener, H. P. M. and S. Piras. 1997. "The Pressure Line of the Aspendos Aqueduct." *Adalya* II: 159-87.

———. 1998a. "The Aspendos Aqueduct and the Roman-Seljuk Bridge Across the Eurymedon." *Adalya* III: 149-68.

———. 1998b. "The Aspendos Aqueduct Research Project First Campaign (1996) The Siphon." Paper read at *XV. Arastirma Sonuçlari Toplantisi II.*

———. 1998c. "The Aspendos Aqueduct Research Project: The Siphon." Paper read at *XVth International Congress of Classical Archaeology*, 12-17 July, at Amsterdam.

———. 2000. "The 1998 Campaign of the Aspendos Aqueduct Research Project." Paper read at *17. Arastirma Sonuçlari Toplantisi - 1 Cilt.*

Keyser, P. 1988. "Suetonius 'Nero' 41.2 and the Date of Heron Mechanicus of Alexandria." *Classical Philology* 83 (3): 218-20.

Klaffenbach, G. 1954. *Die Astynomeninschrift von Pergamon*. Abhandlungen der deutschen Akademie der Wissenschaften zu Berlin. Berlin: Akademie-Verlag.

Knauss, J. 1983. *Wirbelbildung an Einlaufbauwerken: Luft- und Dralleintrag*. DVWK Schriften 63. Hamburg: P. Parey.

Koldewey, R. 1890. *Die antiken Baureste der Insel Lesbos*. Berlin: G. Reimer.

Kootz, M. 1963. *Das Rohr in den Jahrtausenden, Altertum: das Rohr der griechischen Hochdruck-Wasserleitung in Pergamon: Steinmetzzeichen am Loch-Gipfelstein, Berg II*. Berlin: Martin Kootz.

Kottmann, A. 1984a. "Luft in Wasserleitungen - Technisches Wissen aus römischer Zeit." *Schriftenreihe der Frontinus-Gesellschaft* 7: 82-85.

———. 1984b. "Luftblasen als Ursache von Rohrbrüchen." *3R, Rohre, Rohrleitungsbau, Rohrleitungstransport* 23 (1/2): 45-53.

———. 1992. *Druckstossermittlung in der Wasserversorgung*. Essen: Vulkan Verlag.

Kottmann, A. and C. Schmitt. 1980. "Unerklärliche Rohrbrüche - Mögliche Zusammenhänge zwischen Luftblasen, Fliessgeschwindigkeit und Rohrbrüchen in Wasserrohrleitungen." *3R, Rohre, Rohrleitungsbau, Rohrleitungstransport* 19 (1/2): 54-61.

Lanckoronski, K. 1890. *Städte Pamphyliens und Pisidiens*. Vol. I. Prag, Vienna, Leipzig.

Landels, J. G. 2000. *Engineering in the Ancient World*, revised ed. Berkeley: University of California Press.

Larsen, J. D. 1982. "The Water Towers in Pompeii." *Analecta Romana Instituti Danici* 11: 41-67.

Laurenti, M. C. 1987. "Brevi note su alcuni rinvenimenti a Monte Daielli di Alatri." *Archeologia Laziale* 8: 302-06.

Leglay, M. 1976. "Lugdunum," in R. Stillwell, W. L. MacDonald, and M. H. McAllister (edd.), *PECS*. 528-31. Princeton, NJ: Princeton University Press.

Leveau, P. 2001. "Aqueduct Building: Financing and Costs," in D. Blackman and A. T. Hodge (edd.), *Frontinus' Legacy*. 85-101. Ann Arbor: University of Michigan Press.

Lewis, M. 1999. "Vitruvius and Greek Aqueducts." *Papers of the British School at Rome* 67: 145-72.

———. 2000. "Theoretical Hydraulics, Automata, and Water Clocks," in Ö. Wikander (ed.) *Handbook of Ancient Water Technology*. 343-70. Leiden: Brill.

———. 2001. *Surveying Instruments of Greece and Rome*. Cambridge: Cambridge University Press.

Liddell, H. G. and R. Scott (edd.) 1996. *A Greek-English Lexicon*. 9th ed. Oxford: Clarendon Press.

Lindberg, D. C. 1992. *The Beginnings of Western Science*. Chicago: The University of Chicago Press.

Massey, B. S. 1990. *Mechanics of Fluids*, 6th ed. London: Chapman and Hall.

Merckel, C. 1969. *Die Ingenieurtechnik im Alterthum*. Hildesheim: Olms. Original edition, 1899.

Millette, D. M. 1997. *Textual Imaginations: Vitruvius in Archaeological [Re]Constructions*. Website, last update 1997. Available http://www.shef.ac.uk/assem/3/3millette.htm. Access date 22 October 2002.

Minonzio, F. 2004. "Idraulica e idrologia nella *Naturalis historia* di Plinio," in F. Minonzio (ed.) *Problemi di macchinismo in ambito romano*. Archeologia dell'Italia Settentrionale 8. 113-24. Como: Comune di Como.

Morgan, M. H. 1960. *Vitruvius: The Ten Books on Architecture*. New York: Dover Publications.

Mortet, V. 1907. "Recherches critiques sur Vitruve et son oeuvre IV - Vitruve et l'hydraulique Romaine." *Révue archéologique*: 75-83.

Neugebauer, O. 1938. "Über eine Methode zur Distanzbestimmung Alexandria-Rom bei Heron." *Kgl. Danske Videnskabernes Selskab, Historisk-filosofiske Meddelelser* 26 (2): 3-26.

Nikolic, M. 2003. *Three Inverted Siphons and the Problem of Hydraulic Towers*. MA Thesis, Department of Greek and Roman Studies, University of Calgary, Calgary.

Ohlig, C. 2006. "Vitruvs colliviaria und die vis spiritus - (keine) Luft in Wasserleitungen? (!)," in G. Wiplinger (ed.) *Cura Aquarum in Ephesus* Vol. 1. 319-25. Leuven: Peeters.

Ohnuki, A. and H. Akimoto. 2000. "Experimental Study on Transition of Flow Pattern and Phase Distribution in Upward Air-Water Two-Phase Flow Along a Large Vertical Pipe." *International Journal of Multiphase Flow* 26: 367-86.

Oldfather, W. A. 1939. "Tacitus Annals vi.50.4 and 5: Pulsus Venarum and Spiritus." *Classical Philology* 34 (2): 146-7.

Oleson, J. P. 1984. *Greek and Roman Mechanical Water-Lifting Devices: the History of a Technology*. Toronto: University of Toronto Press.

———. 2000. "Water Lifting," in Ö. Wikander (ed.) *Handbook of Ancient Water Technology*. 217-302. Leiden: Brill.

———. 2004. "Well-Pumps for Dummies: Was there a Roman Tradition of Popular, Sub-literary Engineering Manuals?," in F. Minonzio (ed.) *Problemi di macchinismo in ambito romano*. Archeologia dell'Italia Settentrionale 8. 65-86. Como: Commune di Como.

Ortloff, C. R. 1998. "Hydraulic Analysis of a Self-Cleaning Drainage Outlet at the Hellenistic City of Priene." *Journal of Archaeological Science* 25: 1211-20.

———. 2005. "The Water Supply and Distribution System of the Nabataean City of Petra (Jordan), 300 BC- AD 300." *Cambridge Archaeological Journal* 15 (1): 93-109.

Ortloff, C. R. and D. P. Crouch. 2001. "The Urban Water Supply and Distribution System of the Ionian City of Ephesos in the Roman Imperial Period." *Journal of Archaeological Science* 28: 843-60.

Ortloff, C. R. and A. Kassinos. 2003. "Computational Fluid Dynamics Investigation of the Hydraulic Behaviour of the Roman Inverted Siphon System at Aspendos, Turkey." *Journal of Archaeological Science* 30: 417-28.

Owens, E. J. 1991. *The City in the Greek and Roman World*. New York: Routledge.

Peleg, Y. 1999. "Colliviaria at Caesarea," in K. G. Holum, A. Raban, and J. Patrich (edd.), *Caesarea Papers* Vol. 2. Journal of Roman Archaeology Supplements 35. 361-67. Portsmouth.

———. 2000. "The Characteristics of Water Distribution in Roman Towns," in G. C. M. Jansen (ed.) *Cura Aquarum in Sicilia*. 241-6. Leiden: BABesch.

———. 2002. "Vitruvius Book VIII - Hydraulics and Archaeological Evidence," in C. Ohlig, Y. Peleg, and T. Tsuk (edd.), *Cura Aquarum in Israel*. 213-22. Siegburg: Deutsche Wasserhistorische Gesellschaft.

Pollitt, J. J. 1986. *Art in the Hellenistic Age*. Cambridge: Cambridge University Press.

Quilici, G. 2008. "Land Transport, Part 1: Roads and Bridges," in J. P. Oleson (ed.) *Handbook of Engineering and Technology in the Classical World*. 551-79. New York: Oxford University Press.

Radt, W. 2001. "The Urban Development of Pergamon," in D. Parrish (ed.) *Urbanism in Western Asia Minor*. JRA Supplement 45. 43-56. Portsmouth, RI: Journal of Roman Archaeology.

Rathmayr, R. 2000. *Der antike Mensch in der Jahreszeit des Winters*. Hamburg: Dr. Kovac.

Rice, E. F. and A. Grafton. 1994. *The Foundations of Early Modern Europe, 1460-1559*, 2nd ed. New York: Norton & Company.

Rodgers, R. H. 1986. "Copia Aquarum: Frontinus' Measurements and the Perspective of Capacity." *Transactions of the Americal Philological Association* 116: 353-60.

———. 2004. *Frontinus: De aquaeductu urbis romae*. Cambridge: Cambridge University Press.

Rouse, H. and S. Ince. 1963. *History of Hydraulics*. New York: Dover Publications.

Rowland, I. D., T. N. Howe, and M. Dewar. 1999. *Vitruvius: Ten Books on Architecture*. Cambridge: Cambridge University Press.

Saastamoinen, A. 2000. "The Literary Character of Frontinus' De aquaeductu," in C. Bruun and A. Saastamoinen (edd.), *Technology, Ideology, Water: From Frontinus to the Renaissance and Beyond* 31. 15-40. Rome: Institutum Romanum Finlandiae.

Salmon, E. T. 1976. "Aletrium," in R. Stillwell, W. L. MacDonald, and M. H. McAllister (edd.), *PECS*. 36. Princeton, NJ: Princeton University Press.

Sánchez Almonacid, M. 1889. "El acueducto romano de cabeza de Griego." *Boletín de la Real Academia de Historia* 15: 160-70.

Schäfer, J. 1976. "Pergamon," in R. Stillwell, W. L. MacDonald, and M. H. McAllister (edd.), *PECS*. 688-92. Princeton, NJ: Princeton University Press.

Schmidt, W. 1899. *Herons von Alexandria Druckwerke und Automatentheater*. Vol. 1. Leipzig: Teubner.

Schmitz, W. 1978. "Kalksinter im Römerkanal." *Das rheinische Landesmuseum Bonn* 4 (78): 55-57.

Schnappauf, J. 1966. "Luftblasen in Rohrleitungen--vereinfachend betrachtet." *Neue DELIWA-Zeitschrift*: 371-73.

Schulten, A. 1955. "Segóbriga," *RE II A, 1*. 1077.

Schwarz, M. 2006. "Vitruvs geheimnisvolle colliviaria entschlüsselt?," in G. Wiplinger (ed.) *Cura Aquarum in Ephesus* Vol. 1. 327-34. Leuven: Peeters.

Secchi, A. 1864. "On the Ancient Aqueduct of Alatri." *The London, Edinburgh, and Dublin Philosophical Magazine and journal of Science* 28: 406-08.

Şimşek, C. and M. Büyükkolancı. 2006. "Die Aquädukte und das Wasserverteilungssystem von Laodikeia ad Lycum," in G. Wiplinger (ed.) *Cura Aquarum in Ephesus* Vol. 1. 137-46. Leuven: Peeters.

Smith, N. A. F. 1976. "Attitudes to Roman Engineering and the Question of the Inverted Siphon." *History of Technology* 1: 45-71.

Stehlin, K. 1918. "Über die colliviaria oder colliquiaria der römischen Wasserleitungen." *Anzeiger für schweizerische Altertumskunde* 20: 167-75.

Stenton, E. C. and J. J. Coulton. 1986. "Oinoanda: The Water Supply and Aqueduct." *Anatolian Studies* 36: 15-59.

Talbert, R. J. A. (ed.) 2000. *Barrington Atlas of the Greek and Roman World*. Princeton, N.J.: Princeton University Press.

PuTTY 0.58, Cambridge.

Thompson, F. H. 1954. "The Roman Aqueduct at Lincoln." *Archaeological Journal* 111: 106-28.

Tölle-Kastenbein, R. 1990. *Antike Wasserkultur*. Munich: Beck.

———. 1991. "Entlüftung antiker Wasserleitungsrohre." *Archäologischer Anzeiger*: 25-30.

Tybjerg, K. 2004. "Hydraulics in Hero?," in F. Minonzio (ed.) *Problemi di macchinismo in ambito romano*. Archeologia dell'Italia Settentrionale 8. 25-31. Como: Commune di Como.

Usher, A. P. 1954. *A History of Mechanical Inventions*. Cambridge: Harvard University Press.

van Deman, E. B. 1934. *The Building of the Roman Aqueducts*. Washington: Carnegie Institution of Washington.

Villaronga Garriga, L. 1978. "Sobre la localización de Segóbriga." *Gaceta Numismatica* 51: 13-17.

VNC Viewer Free Edition 4.1.2. Real VNC Ltd., Cambridge.

Ward-Perkins, J. B. 1955. "The Aqueduct of Aspendos." *Papers of the British School at Rome* 23: 115-23.

Weber, G. 1898. "Die Hochdruck-Wasserleitung von Laodicea ad Lycum." *Jahrbuch des archäologischen Instituts* 13: 1-13.

———. 1899. "Die Wasserleitungen von Smyrna." *Jahrbuch des kaiserlich deutschen archäologischen Instituts* (XIV): 4-25, 167-88.

———. 1900a. "Die Wasserleitungen von Smyrna." *Jahrbuch des kaiserlich deutschen archäologischen Instituts* 14: 4-25, 167-88.

———. 1900b. "Die Wasserleitungen von Smyrna." *Jahrbuch des kaiserlich deutschen archäologischen Instituts* (14): 4-25, 167-88.

Wikander, Ö. (ed.) 2000. *Handbook of Ancient Water Technology*. Technology and Change in History. Leiden: Brill.

Wilson, A. 2002. "Machines, Power and the Ancient Economy." *Journal of Roman Studies* 92: 1-32.

Winkel, R. 1914. *Abhängigkeit der Wasserbewegung in einer Rohrleitung, insbesondere die Abhängigkeit der fliessenden Wassermenge von der Höhenlage und der Ausbildung des Einlaufes, d. h. des Mundstückes*. Dissertation, Herzogliche Technische Hochschule "Carolo Wilhelmina" zu Braunschweig, Braunschweig.

Woodcroft, B. 1851. *The Pneumatics of Hero of Alexandria*. Website. Taylor, Walton, and Maberly, last update December 1996. Available http://www.history.rochester.edu/steam/hero/index.html. Access date November 2007.

Zschietzschmann, W. 1955a. "Methymna," *RE XV, 2*. 1391-95.

———. 1955b. "Pergamon," *RE XIX, 1*. 1235-63.

Appendix of Copyrighted Images

Figure 0.1: The Harmonious Goblets
Woodcroft, B. 1851. *The Pneumatics of Hero of Alexandria*. Website. Taylor, Walton, and Maberly, last update December 1996. Available http://www.history.rochester.edu/steam/hero/index.html. Access date November 2007.

Figure 0.2: The Inexhaustible Vessel
Woodcroft, B. 1851. *The Pneumatics of Hero of Alexandria*. Website. Taylor, Walton, and Maberly, last update December 1996. Available http://www.history.rochester.edu/steam/hero/index.html. Access date November 2007.

Figure 0.3: A Pipe From which Wine and Water Flow in Varying Proportions
Woodcroft, B. 1851. *The Pneumatics of Hero of Alexandria*. Website. Taylor, Walton, and Maberly, last update December 1996. Available http://www.history.rochester.edu/steam/hero/index.html. Access date November 2007.

Figure 0.4: Valve for a Pump
Woodcroft, B. 1851. *The Pneumatics of Hero of Alexandria*. Website. Taylor, Walton, and Maberly, last update December 1996. Available http://www.history.rochester.edu/steam/hero/index.html. Access date November 2007.

Figure 0.5: Floating Device for Valve Control
Woodcroft, B. 1851. *The Pneumatics of Hero of Alexandria*. Website. Taylor, Walton, and Maberly, last update December 1996. Available http://www.history.rochester.edu/steam/hero/index.html. Access date November 2007.

Figure 0.6: Piston Pump
Woodcroft, B. 1851. *The Pneumatics of Hero of Alexandria*. Website. Taylor, Walton, and Maberly, last update December 1996. Available http://www.history.rochester.edu/steam/hero/index.html. Access date November 2007.

Figure 0.7: Pergamum
Google Earth Plus 4.0.2091 (beta). Google Inc.

Figure 0.8: Pergamum
Radt, W. 2001. “The Urban Development of Pergamon,” in D. Parrish (ed.) *Urbanism in Western Asia Minor*. JRA Supplement 45. 43-56. Portsmouth, RI: Journal of Roman Archaeology, p. 51.

Figure 0.9: Pergamum Inverted Siphon Elevation and Plan
Garbrecht, G. 1978. “Wasserwirtschaftliche Anlagen des antiken Pergamon: die Druckleitung.” *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 60, Abb. 2.

Figure 0.10: Header Tank
Garbrecht, G. 1978. “Wasserwirtschaftliche Anlagen des antiken Pergamon: die Druckleitung.” *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 60, Abb. 4.

Figure 0.11: Anchor Stones for Pipeline
Garbrecht, G. 1978. “Wasserwirtschaftliche Anlagen des antiken Pergamon: die Druckleitung.” *Mitteilungen des Leichtweiss-Instituts für Wasserbau* 60, Abb. 5.

Figure 0.12: Izmir
Weber, G. 1900. “Die Wasserleitungen von Smyrna.” *Jahrbuch des kaiserlich deutschen archäologischen Instituts* 14: 4-25, 167-88, Tafel 3 and *Google Earth Plus* 4.0.2091 (beta). Google Inc.

Figure 0.13: Smyrna
Lewis, M. 1999. “Vitruvius and Greek Aqueducts.” *Papers of the British School at Rome* 67: 145-72, p. 159, Fig. 1.

Figure 0.14: Ancient Methymna
Buchholz, H.-G. 1976. *Methymna: Archäologische Beiträge zur Topographie und Geschichte von Nordlesbos*. Mainz: P. von Zabern, p. 21, Abb. 1.

Figure 0.15: Overlay of Koldewey`s Map on Satellite Image
Buchholz, H.-G. 1976. *Methymna: Archäologische Beiträge zur Topographie und Geschichte von Nordlesbos*. Mainz: P. von Zabern, p. 21, Abb. 1 and *Google Earth Plus* 4.0.2091 (beta). Google Inc.

Figure 0.16: View of Methymna with Koldewey`s Map
Buchholz, H.-G. 1976. *Methymna: Archäologische Beiträge zur Topographie und Geschichte von Nordlesbos*. Mainz: P. von Zabern, p. 21, Abb. 1 and *Google Earth Plus* 4.0.2091 (beta). Google Inc.

Figure 0.17: Alatri
Google Earth Plus 4.0.2091 (beta). Google Inc.

Figure 0.18: Alatri

Bassel, R. 1881. “Antike Hochdruckwasserleitung des Betilienus in Alatri.” *Centralblatt der Bauverwaltung*: 121-2, p. 121 and Merckel, C. 1969. *Die Ingenieurtechnik im Alterthum*. Hildesheim: Olms. Original edition, 1899, p. 561, Abb. 245.

Figure 0.19: Alatri

Lewis, M. 1999. “Vitruvius and Greek Aqueducts.” *Papers of the British School at Rome* 67: 145-72, p. 159, Fig. 1.

Figure 0.20: Brèvenne Aqueduct

Chatenet, C. 2003. *Les aqueducs romains de Lyon*. Website. École Centrale de Lyon, last update September 2003. Available http://chappe.ec-lyon.fr/. Access date 12 May 2006.

Figure 0.21: Mont d’Or Aqueduct

Chatenet, C. 2003. *Les aqueducs romains de Lyon*. Website. École Centrale de Lyon, last update September 2003. Available http://chappe.ec-lyon.fr/. Access date 12 May 2006.

Figure 0.22: Gier Aqueduct, First Stretch

Chatenet, C. 2003. *Les aqueducs romains de Lyon*. Website. École Centrale de Lyon, last update September 2003. Available http://chappe.ec-lyon.fr/. Access date 12 May 2006.

Figure 0.23: Gier Aqueduct, Second Stretch

Chatenet, C. 2003. *Les aqueducs romains de Lyon*. Website. École Centrale de Lyon, last update September 2003. Available http://chappe.ec-lyon.fr/. Access date 12 May 2006.

Figure 0.24: Gier Aqueduct, Third Stretch

Chatenet, C. 2003. *Les aqueducs romains de Lyon*. Website. École Centrale de Lyon, last update September 2003. Available http://chappe.ec-lyon.fr/. Access date 12 May 2006.

Figure 0.25: Yzeron Aqueduct

Chatenet, C. 2003. *Les aqueducs romains de Lyon*. Website. École Centrale de Lyon, last update September 2003. Available http://chappe.ec-lyon.fr/. Access date 12 May 2006.

Figure 0.26: Double Inverted Siphon at Yzeron

Google Earth Plus 4.0.2091 (beta). Google Inc.

Figure 0.27: Tourillons de Craponne

Burdy, J. 2002. *Les aqueducs romains de Lyon*. Lyon: Presses universitaires de Lyon, p. 73, Fig. 35.

Figure 0.28: Tourillons de Craponne
Burdy, J. 2002. *Les aqueducs romains de Lyon*. Lyon: Presses universitaires de Lyon, p. 138, Fig. 61.

Figure 0.29: Erroneous Scale (bottom left) in Previous Publications—Map Overlay on Google Earth Plus
Almagro Basch, M. 1976. "El acueducto romano de Segóbriga." *Revista de Archivos, Bibliotecas y Museos* 79: 875-902, Fig. 1 and *Google Earth Plus* 4.0.2091 (beta). Google Inc.

Figure 0.30: Segóbriga Overview
Google Earth Plus 4.0.2091 (beta). Google Inc.

Figure 0.31: Segóbriga
Abascal, J. M., M. Almagro Gorbea, and R. Cebrián. 2006. "Segobriga: *caput Celtiberiae* and Latin *municipium*," in A. Abad Casal, S. Keay, and S. Ramallo Asensio (edd.), *Early Roman Towns in Hispania Tarraconensis*. JRA Suppl. 62. 184-96. Portsmouth, RI: Journal of Roman Archaeology, p. 184, Fig. 14.1.

Figure 0.32: Segóbriga Aqueduct
Almagro Basch, M. 1976. "El acueducto romano de Segóbriga." *Revista de Archivos, Bibliotecas y Museos* 79: 875-902, Fig. 1 and Abascal, J. M. *personal communication*.

Figure 0.33: Lead Pipe Fragment
Almagro Basch, M. 1976. "El acueducto romano de Segóbriga." *Revista de Archivos, Bibliotecas y Museos* 79: 875-902, Lám. 32.

Figure 0.34: Segóbriga Cistern
Abascal, J. M., M. Almagro-Gorbea, and R. Cebrián. 2005. *Segóbriga*. Madrid: Real Academia de la Historia, p. 33, Fig. 25.

Figure 0.35: *Apodyterium* of Theatre Baths
Abascal, J. M., M. Almagro-Gorbea, and R. Cebrián. 2005. *Segóbriga*. Madrid: Real Academia de la Historia, p. 17, Fig. 8.

Figure 0.36: Monumental Baths
Abascal, J. M., M. Almagro-Gorbea, and R. Cebrián. 2005. *Segóbriga*. Madrid: Real Academia de la Historia, p. 28, Fig. 21.

Figure 0.37: Aspendos
Google Earth Plus 4.0.2091 (beta). Google Inc.

Figure 0.38: Plan of the Aspendos Aqueduct
Kessener, H. P. M. and S. Piras. 1997. “The Pressure Line of the Aspendos Aqueduct.” *Adalya* II: 159-87, p. 183, Fig. 22.

Figure 0.39: Plan of Header Tank at Aspendos
Kessener, H. P. M. and S. Piras. 1997. “The Pressure Line of the Aspendos Aqueduct.” *Adalya* II: 159-87, p. 183, Fig. 20.

Figure 0.40: Plan of Tower Bases
Kessener, H. P. M. and S. Piras. 1997. “The Pressure Line of the Aspendos Aqueduct.” *Adalya* II: 159-87, p. 176, Fig. 5.

Figure 0.41: Example Profile for Air Blocks
Jordan, T. D. 1984. *A Handbook of Gravity-Flow Water Systems*. London: Intermediate Technology Publications, p. 194, Fig. B-1.

Figure 0.42: System in Equilibrium with Air Blocks
Jordan, T. D. 1984. *A Handbook of Gravity-Flow Water Systems*. London: Intermediate Technology Publications, p. 195, Fig. B-2.

Figure 0.43: Detail of Multiple Air Blocks
Jordan, T. D. 1984. *A Handbook of Gravity-Flow Water Systems*. London: Intermediate Technology Publications, p. 198, Fig. B-4.

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