THE AQUEDUCTS OF ANCIENT ROME

by

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I declare that

The Aqueducts of Ancient Rome is my own work and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references.

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SIGNATURE

(MR E J DEMBSKEY)

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Chapter 1

INTRODUCTION

1.1 Introduction

It is self-evident that all human settlements, whether a village, town or city, need water for drinking, sanitation and agriculture. As Landels (2000:34) states: *"Water supply represented one of the most serious problems for Greek and Roman urban communities"*. Three factors influence the amount of water required, namely 1) the size of the population, 2) the use to which water is put and 3) the efficiency of the water transport and distribution system. A city like Rome, which had an estimated population of more than a million in imperial times (for AD 226 and earlier), used huge amounts of water for entertainments like the baths and naturally had water leakage problems in their water distribution systems, therefore needed a copious supply, more than the Tiber and local springs could provide. Indeed, even during the early days of Rome, the Tiber was rarely used as a source for potable water, as it had been polluted relatively early by waste from human settlements (Heiken, Funiciello & De Rita, 2005:136)[1]. It is also likely that the harbour facilities made it impractical to use the Tiber water in the immediate vicinity [2]. Rome solved the problem of supply by diverting water from the volcanic highlands of the Alban Hills to the southeast, the Sabatini

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[1] This is not accepted without debate. See Chapter 6.5

[2] This is a far more likely explanation.

volcanoes to the northwest and from the Apennine mountains in the north and east (see Figure D.11). Rome is probably unique in the ancient world in regards the quantity of water brought in. Strabo (5.3.8) tells us that veritable rivers of water flowed through Rome. To quote:

> *So much, then, for the blessings with which nature supplies the city... water is brought into the city through the aqueducts in such quantities that veritable rivers flow through the city and the sewers; and almost every house has cisterns, and service-pipes, and copious fountains, with which Marcus Agrippa concerned himself most...*

Strabo is of course not referring to natural rivers, but to the artificial rivers created by the hydraulic engineering skills of the Romans, known as *aqueducts*, from the Latin *aquae ductus*, "conveyance of water". Indeed, there is probably no monument to the hydraulic engineering of the ancient world that compares with Roman aqueducts in terms of systemic complexity, engineering and social- and environmental-impact. It can be argued that the aqueducts were not only functional but also amongst the most pleasing and satisfying of the ancient monuments. This was not missed by the practical Roman mind. Pliny the Elder wrote:

> *... but if anyone will note the abundance of water skilfully brought into the city, for public uses, for baths, for basins, for house, runnels, suburban gardens, and villas; if he will note the high aqueducts required for maintaining the proper elevation; the mountains which had to be pierced for the same reason; and the valleys it was necessary to fill up; he will consider that the whole terrestrial orb offers nothing more marvellous.*

Frontinus was even more effusive in his praise (1.16):

> *With such an array of indispensable structures carrying so many waters, compare if you will, the idle Pyramids or the useless, though famous works of the Greeks.*

It is difficult to establish how many aqueducts the Romans built, the number usually estimated at between eleven and nineteen, but with most scholars agreeing on the number eleven. In his *The Aqueducts of Ancient Rome*, Thomas Ashby fixes the number at eleven, stating that the "extra" aqueducts are branches and not separate aqueducts (Ashby, 1935. See Heiken, Funiciello & De Rita, 2005:147 for commentary). These eleven aqueducts, known as the major aqueducts, were built between 312 BC and AD 226. An unknown number of minor aqueducts, although probably between eight and twelve in number, may have been built during the same time. The evidence is scant and inconclusive. The estimated total length of the major aqueducts is between 448 and 502 kilometres. The shortest aqueduct, Appia, was only 16 kilometres long and the longest, the Marcia, was 91 kilometres long. Hodge (2002:347) gives an estimated total output of 1,127,220 cubic metres of water per day for the Roman aqueducts. One can deduce then, that when the population may have been well over a million[3] (see Figure D.5 for a comparison of water supply and population density), the distribution system would have been able to provide more than one cubic metre[4] of water per day for each inhabitant of the city of Rome. By comparison, New York City consumes 5,550,000 million cubic metres of water per day for six million inhabitants (not including commuters who work but do not live in the city) (Elert, 2004). According to the Rand Water Board (2007:5), they supply 3,550,000 million cubic metres of water to 11 million people in Gauteng daily. Thus, both New York and Gauteng provide less than 1 cubic metre of water per person per day. According to the evidence, the Roman water supply exceeded this.[5]

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[3] It is difficult to determine the number of Roman inhabitants. We have no idea of the number of slaves in Rome, beyond the impression that they increased in number in Italy during the last two centuries of the republic. Estimates are based on chance comments by authors and the Roman census (Morley, in Rosenstein & Morstein-Marx, 2006:321). The figures for those receiving the grain dole are particularly useful.

[4] A cubic metre of water is 1000 litres of water.

[5] Patterson, in Rosenstein & Morstein-Marx (2006:352), states that republican Rome's poor had poor access to potable water. In the late republic and empire this is not likely

A reliable water supply to the hub of the Roman world, both republic and empire, is one of the many factors in its success and longevity. Without a steady and reliable supply of water to animate the fountains, slake the thirst, fill the baths and flush the toilets[6] of the citizens of Rome, the wheel of Empire would not have turned smoothly, and it can be argued that the Romans would not have risen to the pre-eminent Western civilisation of the time without it. While this was not a feature of any other empire, the Roman empire was in many ways more complex than previous empires; it was larger, more administratively complex, and endured for a longer time than most. Even after the so-called fall of the empire, the city of Rome continued to survive, and even thrive. Of course much of the water delivered to Rome was not intended for use as potable water, but for entertainment[7]. By the end of the 4th century A.D. Rome had eleven large public baths (*thermae*, 965 smaller bathhouses and 1,352 public fountains (Heiken, Funiciello & De Rita, 2005:129). Each of these would no doubt require a minimum of several thousand litres of water per day [8]. Of the fountains and the quality of the water, Galen wrote in 164 AD (Morton, 1966:31):

> *The beauty and number of Rome's fountains is wonderful. None emits water that is foul, mineralised, turbid, hard or cold.*

While the focus of this study is on the aqueducts that supplied Rome, by necessity occasional reference will be made to the aqueducts that predate the Romans, and the aqueducts made by the Romans throughout their empire. This serves to demonstrate the evolution of the aqueducts, and

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to be true.

[6] Hodge (2002:270) states that the public toilets may have been the commonest use of aqueduct water in Rome.

[7] It is interesting to contemplate the fact that many forms of technology that are developed for one purpose are often used by the entertainment industry.

[8] A modest sized bath, 10 by 5 by 1.5 metres, would take 75 cubic metres of water to fill. As this water was continuously replaced, daily use could exceed 150 to 225 cubic metres per day rather easily. Some of the baths must have consumed water at orders of magnitude greater than this.

allows for a comparison between practice at Rome and elsewhere in the Roman world[9]. As with many aspects of Roman culture and technology, the Greeks served as progenitors. Exploring these various aspects will give a rounded account; the Roman aqueducts are not necessarily representative of the hundreds of other aqueducts that were built, nor were they created in a vacuum.

It is within this context that this study has been undertaken. The research will include the technical aspects of aqueduct construction and maintenance. The aqueducts in their political and social context is briefly examined. The major events that made the construction of the aqueducts possible are analysed. For example, how the Roman conquest of Latium, Samnium, Campania and Etruria provided the stability and regional control that was needed for the construction of the aqueducts. The view is put forward that the development of the aqueducts to their neglect and ruin is a reflection of the Roman world in miniature, the rise and fall of Roman hegemony. In addition, a chapter will be devoted to reflection upon the research itself, including an analysis of the problems and suggesting solutions for historians when attempting research far removed from the subject of that research.

Construction, whether it be of roads, bridges, buildings or aqueducts requires four elements: the higher authorities to make the initial decisions, technical experts to put these into practice, material to build with and labourers to do the actual work (O'Conner, 1993:36). So it must be born in mind that when it is said that, for example, the *censors*[10] Ap. Claudius and C. Plautius built an aqueduct,[11] it was not they that designed or physically laboured on it. It means that he decided and directed (or was directed by a higher authority) the construction of an aqueduct. Of course, this is not

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[9] Rome adopted many innovations and improved on them, and in turn, these were adopted in the provinces and beyond.

[10] A *censor's* duties included he administration of state finances, including the erection of all new public works.

[11] The Aqua Appia, 312 BC.

to imply that the person referred to did not have the technical competence to build an aqueduct. Appius Claudius was an accomplished man, as were most in positions of authority. After all, the Roman system did not allow individuals to reach the highest ranks without prior training and experience. Indeed, the *cursus honorum*, or political path, existed as early as the fourth century BC, and may be one of the stabilising and progressive features of the Roman political system.

1.2 Objectives

This thesis will examine the eleven main aqueducts that fed the city of Rome; how they were made, what they were made of, when and how they were repaired, the tools that were used to make them, the skills needed to make them and how the prevailing political climate that existed at the time influenced the construction of each aqueduct. As far as possible, the distribution of water from each aqueduct will be examined, but this aspect may be considered an insoluble problem (Evans, 1997:2).

One area that is often neglected in the study of Roman aqueducts is the minor and "missing" aqueducts in Rome. Ashby, in particular, makes mention of many aqueducts that are known only by inscription. His source seems to be the *Notitia* and the *Curiosum* (Ashby, 1935). Some of these refer to aqueducts known by other names, or branches from major aqueducts, or even minor waterways that barely warrant the name aqueduct. There are a number, though, of which nothing is known. It is time to revive the study of these, even if the goal is simply to begin the synthesis of the work of the last 70 years into a single document.

To summarise the objectives:

- To discuss the technical aspects of Roman aqueduct construction
- To research the so-called minor Roman aqueducts

- To research the problem of the partial, but premature, collapse of the Aqua Claudia
- To discover the prevailing political climate during the time each aqueduct was constructed
- To reflect on the aqueducts as indicators of the health of the Roman republic and empire, the argument being that the health of the aqueduct system was a reflection of the health of the Roman state
- To reflect on the role of the aqueduct system in the decline of the Empire
- To reflect on the research process itself
- To produce a list of important Roman aqueduct related inscriptions, with *CIL* numbers when available

1.3 Conclusion

The importance of civil infrastructure to the Roman republic and empire is a worthy subject of study. Where literature fails us, the enduring remains of Roman engineering serve as a reminder of the grandeur that was Rome, and simultaneously warns us that technology is not always the answer to social problems, and that technology can fail and break when society lacks the resources and will to maintain it. When a society has become accustomed to a particular way of life, a cultural momentum or resistance to change is created. When the technology fails, the society can fail too.

The thesis consists of the following chapters.

Chapter 2 deals briefly with the methodology employed in this study.

Chapter 3 deals with primary, secondary and material resources. The evidence of the ancient authors will be examined, the opinions of modern authors discussed and, when possible, the extant epigraphical, numismatic and archaeological remains examined [12].

Chapter 4 deals with the tools, construction skills and surveying skills used in Roman construction. It is worth noting that the majority of tools are not unique to the construction of aqueducts, but are the common tools that were employed by the Romans to build roads, bridges and buildings. Related skills, such as mathematics, are covered in brief.

Chapter 5 examines the various elements used in the construction of aqueducts, including bridges, siphons, tunnels, *cippi*, settling tanks and so forth. Not all of the elements are typical of Rome's aqueducts, but some discussion of each is included to build the argument that the Romans knew more about hydraulic engineering than sometimes they are given credit for.

Chapter 6 discusses the 11 major Roman aqueducts and the evidence for smaller and "missing" aqueducts. This discussion will include water source and quality, a brief history of each aqueduct, discussion of notable elements and (as far as possible) the use and distribution of each aqueduct's water. The minor aqueducts are barely mentioned by the ancient sources, and we rely almost exclusively on epigraphical and archaeological evidence, especially the *Curiosum* and *Notitia*.

Chapter 7 reflects on the research process. The difficulties experienced by researchers when the subject of their research is not at hand is a factor that must be recognised and controlled for.

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[12] As Evans (2005:37) points out, there is a danger of over-reliance on the written sources instead of undertaking empirical research. With this in mind, and where possible the remains of the Roman aqueducts will be considered. A study of the material remains may illuminate many points that have otherwise been obscured by the ideology of the ancient writers we so typically rely on.

Chapter 8 is the conclusion of the study. Recommendations for further study will also be made.

The appendices contain maps, tables, the inscription reference, figures and selected illustrations of sections of Roman aqueducts, tools and technological artefacts.

Chapter 2

METHODOLOGY

2.1 Introduction

A strictly analytical approach will be used here. A consequence of this is the acceptance that the historical process is not moving in any one direction, towards any goal or end; there is no hidden pattern to be discovered. According to Windschuttle (1997:177) the task of the historian is not to search for some theory that will reveal all, nor some teleology that will explain the purpose of past events and things. Rather, the task is to reconstruct the events of the past in their own terms. As historical events "grow by force of circumstances" (Fuller, 2003:122) and not through some coherent set of laws, this discussion will not look for reason or meaning beyond that which can be gleaned from the evidence. This does not mean that no analysis will be performed, but rather that it will be constrained by the facts and will not be driven by one ideology or another. The post-modern, relativist view of history as a narrative that is situated for the purpose of making sense of the world is firmly rejected in favour of the scientific method (Gross & Levitt (1998), Stove (2006), Ellis (1990), Windschuttle (1997) and Kimball (2002)). While it is true that history cannot be scientific in the sense that it is subject to repeatable identical experiments under controlled conditions (Bispham, in Rosenstein & Morstein-Marx, 2006:47), it can be scientific by principle, by striving for objectivity and the empirical determination of facts. Repeated literary analysis from different perspectives provide interesting intellectual titbits which may illuminate some aspect of the point in space and time in which the analysis was performed, it does not reveal anything definitive about what actually happened. With this understanding, the basis for this research will naturally begin the works of Frontinus and Vitruvius, and then move to the evidence gleaned from other ancient authors, coins, archaeological remains and inscriptions. Due to logistical difficulties, inscriptions will mainly be drawn from *Corpus Inscriptionum Latinarum* (*CIL*). This is an especially important resource, as ready access to some material, such as inscriptions and the aqueducts themselves, is not always possible. Similar difficulties are faced when examining the numismatic evidence.

Middleton (1892a:17) classifies the sources of information available for the study of Rome as follows.

- Classical writers
- Inscriptions, coins and other existing remains
- The regionary catalogues and other documents of the decadence and middle ages
- Works from the fifteenth century to the 19th century
- Modern works

The major ancient literary sources for information on the aqueducts are Vitruvius (1st century BC)[1] and Frontinus (c. AD 34 - 104). A number of other authors mention the aqueducts, but they are usually not of great depth and are often derived from Vitruvius and Frontinus. One exception might have been Pliny the Elder (AD 23/4 - 79) who makes interesting and original

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[1] As far as possible the Penguin Dictionary of Ancient History is used when dating individuals. In the case of Roman Emperors, the span of their lives is shown, not of their rule.

comments in his *Natural History.* Unfortunately, though interesting, Pliny is not always reliable[2], and most of his output is lost. The non-literary sources consist of a great number of inscriptions, a few coins and the aqueducts themselves. The aqueducts are actually remarkably revealing, and much can be learnt by examining their ruins.

Where possible the material remains of the Roman aqueducts will be considered. A study of the material remains may illuminate many points that have otherwise been obscured by the ideology[3] or ignorance of the ancient writers (or modern) we so typically rely on. Alas, few modern writers have the luxury of time and unlimited finances that would free them to indulge in the years of work it would take for a thorough examination of the remains. Thus a balanced approach between the remains, records thereof, the ancient authors and modern authors must be attempted. A number of visual works, such as those by Piranesi, offer interesting insights into the ruins, especially after a century of radical urban change in Rome.

A small number of relevant coins were minted. These are useful artefacts because they help corroborate evidence for dates, and may on occasion be the only firm evidence for this purpose. They are also useful in helping us assess ancient attitudes towards the aqueducts. These will be consulted when practicable. However, this task will be given a low priority, as the coins are rare and difficult to view, and no single source for this numismatic source exists. In addition, coins from the Republican period are not as reliable as coins from the Imperial period. This is due to the fact that there was less central control of the issue, moneyers had more leeway in the republic.

The *CIL* is a comprehensive listing of most, if not all, the known classical Latin inscriptions. Volume six deals with inscriptions found within the

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[2] If Pliny the Younger is to be believed, Pliny's judgement is likewise suspect; he died while lingering to study the Vesuvian eruption.

[3] See Bispham, in Rosenstein & Morstein-Marx (2006:30), for a discussion of idealogical bias in ancient literature.

city of Rome itself, and so is an important work for reading the primary source material without having to spend a number of years gathering it. The *L'Année Épigraphique*, published annually, is also a useful source. It began as a supplement to *CIL*, serving as a central location for inscriptions discovered or edited after the publication of the Corpus. The bulk of relevant inscriptions are reproduced in modern works; however, *CIL* is useful in that it preserves the look of the inscriptions.

By regionary catalogues, Middleton refers mainly to the *Notitia* and *Curiosum* are lists of the chief buildings and monuments in each of the regions of Augustus. They standard works were compiled in the fourth century. While useful, they introduce new problems of interpretation.

With the revival of interest in classical civilisation in the fifteenth century a number of books on the subject of the Eternal city were published. As Middleton (1892a:24) states, these works are not remarkable for the scholarship or power of accurate and critical research, but they are valuable to the modern scholar both for the accounts of discoveries and their numerous illustrations of buildings which have now either wholly or in part disappeared. An example of this is a map from 1472 (see Figure D.1) shows a part of the *Arcus Caelemontani* behind the Colosseum, which no longer exists. Sources such as this are invaluable in reconstructing details.

There has been considerable interest in Roman aqueducts and therefore there are a large number of modern books and papers on the subject, foremost being the work of Ashby, Van Deman, Evans and Hodge. As Evans (1997:1) states, the work of Ashby and Van Deman will never be superseded, because much of the physical evidence they documented has now been lost as a result of Rome's rapid expansion into the countryside after World War II (and no doubt the war itself took some toll on the city). This makes it a necessity to use these works.

Ashby has written or contributed to a number of standard works in the field. *The Aqueducts of Ancient Rome*, though dated, is an invaluable work which provides an excellent summary of our knowledge of the aqueducts in the late 1930s. Until Hodge, this was the standard work on aqueducts, and remains an extremely valuable work, especially considering Evans' point above. Ashby is for all intense purposes, the beginning of any undertaking to research the Roman aqueducts. The *Topographical Dictionary of Ancient Rome* by Samual Ball Platner and Ashby is an indispensable work; it provides much information and many references that help the researcher with all aspects of the study of aqueducts and other buildings in Rome. Likewise, his *The Roman Campagna in Classical Times* is of great help in understanding Rome's water management in the days before aqueducts.

Richardson's *New Topographical Dictionary of Ancient Rome* to some extent succeeds Platner and Ashby's dictionary. The argument can be made that both are required references when studying the city of Rome. Although there is no substitute for actually examining the sites first hand, Nash's *Pictorial Dictionary of Ancient Rome* goes some way towards understanding the physical space when such luxury is unavailable.

No research can be conducted without reference to *Roman Aqueducts and Water Supply* by Trevor Hodge. Hodge's work is updates Ashby's and answers many of the questions left by the latter's work thanks to the benefit of almost a century of archaeological and historical research. The only shortcomings are perhaps its sparse attention to geological and historical detail. Hodge's bibliography is comprehensive, and serves as a good starting point for research on aqueducts.

J.G. Landel's *Engineering in the Ancient World* is considered canonical by any researcher interested in the subject matter of Roman and Greek engineering. Though he devotes only a single chapter to aqueducts, the entire book provides a solid foundation for any study of Roman engineering.

Wasserversorgung im antiken Rom, compiled by the Frontinus-Gesellschaft, is a modern treatment of the subject that complements the work of Hodge and Ashby. Of especial interest is W. Eck's *Die Gestalt Frontins in ihrer politischen und sozialen Umwelt*, which makes many illuminating points about the world in which Frontinus lived, details that are missing in Hodge and outdated in Ashby.

Raffaello Fabretti's *De aquis et aquaeductibus veteris Romae* is an essential work, and provides some literary evidence found no where else. However, this work may have to be treated with caution as Fabretti seems to make sweeping statements without evidence to substantiate them.

Beyond these canonical works, there exists a wealth of books and journal articles too numerous to mention individually, which will where relevant, be incorporated in the discussions to follow. Further references to the aqueducts in the ancient literature will be sought as a matter of course.

As to the issue of place names; within the text the most logical form of the name will be used, i.e. either the modern or the Roman depending on the context. A short table of place names, indicating the Roman and modern names will be included in the appendices. As not all ancient Roman places have been positively identified, the most likely candidate (if known) will be indicated, with a note to indicate this fact.

2.2 Conclusion

The method followed in this thesis is to study the primary literature (in translation), transcribed inscriptions and if possible, coins or coin illustrations and material remains of the aqueducts themselves. Recourse is made to photographs, etchings and paintings when these prove illuminating. Where access to the remains is not possible, which it usually isn't, standard references will be used. Due to logistical constraints the luxury of examining the remains will probably have to be forgone. The numismatic evidence is unfortunately scant, and not without controversy. In addition, secondary material will be referred to; the arguments of modern scholars are indispensable. This is especially true when it is realised that a multi-disciplinary approach is required when studying the Roman water system.

Chapter 3

SOURCES

3.1 Introduction

This chapter examines the surviving evidence for the aqueducts. This includes literary, numismatic and epigraphic evidence. When dealing with a complex system such as the aqueducts of Rome in a remote time, it is expected that there will be gaps or inaccuracies in these sources. Thus, even though the archaeological evidence has many gaps and mysteries, it will also be considered.

When studying the topography of an ancient city that has been continuously occupied for more than 2500 years the number and nature of problems are many and complex. Most of the literary, numismatic and epigraphic evidence is no longer extant. Of the material that is extant, the reliability is variable and the interpretation often subjective. This is either because of deficiencies in the original material, conflict between the original purpose of the material and the purpose to which we wish to put it and through transcription and translation error. The archaeological evidence is often no longer extant, or altered in such a manner that poor data is retrieved, or extant but inaccessible, perhaps due to proximity to modern buildings and infrastructure or other right of way issues.

The best strategy would be to examine the extant ruins as far as possible, and then fill in the gaps as far as possible from the literary evidence. This will be better than the reverse, beginning with the literary material, because it avoids to a large extent the problems caused by biased interpretations of the literary material and erroneous beliefs caused by deficiencies in the literary material. However, that approach is not without its own problems, as much of the material is lost, and much of what remains is inaccessible.

3.2 Literary evidence

The major literary sources for information on the aqueducts are Vitruvius (1st century BC) and Frontinus (c. AD 34 - 104). Vitruvius speaks in general about Roman architecture[1] and includes a chapter on aqueduct technology, while Frontinus addresses the aqueducts of Rome specifically. A number of other authors mention the aqueducts, but such mention is usually not of great depth or usefulness and are usually derivative of Vitruvius and Frontinus, but at least provide corroborative evidence. One exception, Pliny the Elder (AD 23/4 - 79), whose wide field of interest and interesting and original comments in his books *Natural History* provide much information from other sources otherwise lost. As previously mentioned, Pliny is not always a reliable source, and little of his corpus has survived. Indeed, early Roman history is built on slender foundations. Roman history involved considerable willingness to invent and embroider (Bispham, in Rosenstein & Morstein-Marx, 2006:34). While making for enjoyable reading, this decreases the usefulness of many texts.

The non-literary sources consist of a great number of inscriptions, a few coins and the aqueducts themselves. The aqueducts are actually remarkably revealing considering how little survives, and many facts can be determined by examining their ruins. Some of these facts show that practice did not

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[1] The definition of Roman architecture is broader than our own, and includes engineering and even sundials and clocks.

always mirror Vitruvius, and teach us not to take his word blindly.

Vitruvius

Vitruvius (fl. 1st century BC) was a Roman architect who worked for both Caesar and Augustus, but the only building he mentions as his own is a basilica at Fanum. Vitruvius does not seem to have had any connection to the major works of his time, and his fame is derived entirely from his treatise *De Architectura* in ten books, also known by its English title, *On Architecture.* The *De Architectura* was probably written between 30 and 27 BC, and possibly as late as and 23 BC (Aicher, 1995:7 and Landels, 2000:209). Vitruvius is unknown to the authors of his day, so virtually everything we know about him must be drawn from the *De Architectura.* Even his full name is not known with certainty. The words *Vitruvii de Architectura* head all the most reliable texts, and he is known simply as "Vitruvius" to Pliny and Frontinus. There is some evidence to suggest his cognomen may have been "Pollio", from a single reference in a building manual from the early third century known as *De Diversis Fabricis Architectonicae* by M. Cetius Faventius. This is far from certain and not universally accepted (Plommer, 1973:1). The translation could refer to two authors called, the first being Vitruvius and the second Pollio, and not one by the name of Vitruvius Pollio. His praenomen is reported variously as Aulus, Lucius and Marcus. Vitruvius was clearly a freeborn citizen, though probably not of equestrian class. He claims that he was given a broad "liberal arts" education (6.3.4) as well as a professional education. His early adult life was probably spent in the military. Indeed, Vitruvius was appointed, after Caesar's death, to be in charge of the construction and repair of catapults (Landels, 2000:209). This was a responsible position not given lightly, and shines a positive light on Vitruvius.

De Architectura is an example of a hybrid type of literature that was common in the last century or the Republic. It is essentially a technical handbook with literary pretensions (Hodge, 2002:14). Unlike many ancient authors (especially historians), Vitruvius does not denigrate the work of other authors but rather lavishes praise on them. The *De Architectura* is one of many examples of Latin texts that owe their survival to the palace scriptorium of Charlemagne in the early ninth century[2]. The mood of the preface is one of the strongest reasons for dating the *De Architectura* to the decade after Actium (31 BC). Vitruvius states that he is writing at that particular time because Octavian had previously been occupied with *"Taking possession of the world."* (1.1). A period of peace had brought about considerable building activity. Vitruvius wrote his text when, as he put it, *"I perceived that you were solicitous ... for the construction of suitable buildings"* (1.3). The *De Architectura* was not the major architectural handbook of its day, but it's clear Vitruvius was hoping it would be. The books themselves are remarkably objective and comprehensive, though prescriptive rather than descriptive. The importance of the *De Architectura* is twofold. First, it is a rare survivor from a category that was once numerous and important, the technical manual. Secondly, as Vitruvius' definition of an architect is wider than the modern definition, it gives us a good idea of a wide variety of Roman engineering practices. Among interesting concepts contained in the *De Architectura*, Vitruvius declares that quality depends on the social relevance of the artist's work, not on the form or workmanship of the work itself. Vitruvius studied human proportions (third book) and his system of human proportions were later encoded in a very famous drawing by Leonardo da Vinci[3]. Indeed, the *De Architectura* was very influential in the Renaissance. The 16th century architect Palladio considered Vitruvius his master and guide, and made some drawings based on his. Despite the praise heaped upon Vitruvius' shoulders, it must be recalled that most of the recommendations in the *De Architectura* were his, and not a true reflection of actual Roman practice (see Middleton (1892) and Plommer (1973)).

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[2] This activity of finding and recopying classical manuscripts is called the Carolingian Renaissance.

[3] Homo Vitruvianus

Hodge (2002:14) states that Book 8, the book that covered water engineering, is perhaps Vitruvius' worst book, and may have been an imperfect summary from other, possibly Greek, sources. It is possible that Vitruvius did not fully understand the material he copied. A reading of Book 8 partially supports Hodge's critique, but it is perhaps unfair to hold Vitruvius to a technical standard so far above that of his contemporaries.

Vitruvius asserted that a structure must exhibit the three qualities of *firmitas*, *utilitas* and *venustas* - that is, it must be strong or durable, useful and beautiful or graceful (1.3.2). The aqueducts, being mostly underground, usually do not exhibit *venustas*. However, when above ground, it can be argued that they do. However, they perhaps do not show as much *firmitas* as the Romans would have liked.

According to Plommer (1973:28), two later authors, Palladius Rutilius Taurus Aemilianus and M. Cetus Faventinus, wrote books similar to Vitruvius' books. However, they are mostly derived from Vitruvius; Faventinus directly from Vitruvius and Palladius from Faventinus. Both of these authors contain sections on aqueducts, but lack the grasp of Hellenistic science that Vitruvius had. In both cases their works are technically poorer. Faventius seems to show a decline not only from Hellenistic skills, but also from Roman (Plommer, 1973:29). His addition of wood as a viable material for aqueduct channel construction may also show a difference in the mindsets between Vitruvius' era and Faventinus' era. Vitruvius, living in a more optimistic and vigorous time, advocated building for the long term, while Faventinus seems to have been more pessimistic and focussed on the short-term.

While Palladius can easily be dismissed as a source, Faventinus may reward a careful reading. He was perhaps a more experienced builder than Vitruvius. He certainly seemed to have greater empirical knowledge of some building materials, such as lime (Plommer, 1973:93). However, he seems not to have studied outside his probable area of practical expertise. For example, the laying of mosaic floors had advanced since Vitruvius' time, but Faventinus follows Vitruvius very closely (Plommer, 1973:99). This suggests that Faventinus knew little of the actual craft.

Sextus Julius Frontinus

We know little of the Roman politician and engineer Frontinus (c. AD 34 - 104). His full name was Sextus Julius Frontinus, so he belonged to a family of the Julii. Tacitus speaks of him as *praetor urbanus* in 70 AD, so we may infer that he was born in approximately AD 34 or 35. He served under both Nerva (c. AD 30 - 98) and Trajan (AD 53 - 117). In AD 70 he was city *praetor*, and according to Tacitus (*Hist.* 4.39), Frontinus resigned this post. He was appointed *consul* three times, first in 73/4, again in 98 [4], and for a third time in 100. As a governor of Britain (74-8) he subdued the Silures and founded the legionary camp at Exeter. When appointed *curator aquarum*[5] by Nerva in 96 he began a study of the Roman water supply[6] that still survives as *The Aqueducts of Rome.* He wrote a number of other books, but only the *Strategemata* survives relatively intact. Various other fragments do survive, usually as additions by other authors into their writings. His writings on land surveying betray the teachings of the Alexandrian school of mathematics, and it is possible that he was educated in that city. Vegetius used Frontinus' lost book on Greek and Roman warfare, but it is not clear to what extent. It is not possible to say how long Frontinus held the office of *curator aquarum*, but as he died in about AD 103 it is probable that he held it for the remaining years of his life (see Landels, 2000:211 and Evans, 1997:53). Interestingly, Pliny the Younger (c. AD 61 -112), who succeeded Frontinus as *augur* in AD 103, was Pliny the Elder's nephew and adopted son.

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[4] As *consul suffectus.*

[5] Essentially, the "head of the water board"'

[6] Only nine of the eleven major aqueducts had been built by the time Frontinus took office

Though we know little of Frontinus, his personality emerges through his work in no ambiguous fashion. He stands out as a proud and honourable Roman devoted to his emperor and his duty charged with immense responsibility. Martial gives us a picture of Frontinus spending his leisure days in a pleasing environment (
textitEp. 62. See also 48). Pliny writes of appealing to him to help settle a legal dispute. Several inscriptions mention Frontinus, one from Germany dedicated by Julia Frontina, possibly his daughter. An inscription near the Vetera Castra is dedicated to Jupiter, Juno and Minerva in recognition and thanks for the recovery of Sextus Julius Frontinus from illness. A lead pipe found near Via Tiburtina is inscribed *SEXTIULIFRONTINI.* Little evidence, but perhaps enough to show that Frontinus was a well-respected and important. Frontinus himself presents us with two contrasting images. On one hand we have Frontinus the patrician, owning villas near the sea at Formiae and Terracina. He followed the conventional career of the Roman aristocrat, the *cursus honorum.* Then, having obtained the highest rank in his early sixties, he took a totally different and, according to Landels, an apparently less exalted commission. Frontinus points out that the health of the whole urban community relied on the efficient management of the water supply and that the office had been held by ”some of the most outstanding men of the state”. It is possible that he was chosen because of his seniority, which would have given him the authority to check corruption and raised him above any need to be involved in it (Landels, 2000:212).

We do not know how long Frontinus held the office of *curator aquarum*, but we do know that he became head of a commission of public expenditures and *consul suffectus* in 98 AD. It is not likely that he was *curator aquarum* for more than two to three years.

Frontinus was unusual in that he did not consider the technical details of water engineering as beneath his dignity, as perhaps many Roman aristocrats would have done. His first action on becoming the curator aquarum was to make a detailed personal inspection of the entire aqueduct system and to compile his treatise on the essential technical details. The reason he gives for doing so show him as a conscientious public servant and a shrewd officer with the experience of commanding men. He wrote:

> *I have always made it my principle, considering it to be something of prime importance, to have a complete understanding of what I have taken on. For I do not think there is any other surer foundation for any kind of undertaking, or any other way of knowing what to do or what to avoid; nor is there anything more degrading for a man of self-respect than to have to rely on the advice of subordinates in carrying out the commission entrusted to him.*

While Frontinus' *Aqueducts of Rome* is a valuable repository of information concerning Roman aqueducts, it is far more than that. It gives a picture of a faithful public servant called to an office that had long been plagued with abuse and corruption. Nerva and Trajan aimed to correct the abuses that were rampant under the rule of Domitian (AD 51 - 96), and they found in Frontinus a loyal champion of their reforms. He studied with the spirit of a true investigator, displaying scrupulous honesty and fidelity. It is Frontinus that gives us much of the statistical data usually cited on the Aqueducts, though some of his figures are very doubtful (Scarre, 1999), the method Frontinus used was always sound within the parameters of current knowledge. It is probable that the only technical knowledge of water engineering Frontinus had was derived from his own reading, mainly from Greek authors who dealt with elementary principles, and perhaps from his predecessor. However, his military experience, which included the command of men, problems of finance, administration and logistics, would have prepared him well for the task of handling a large organisation. The difficulties of the office of the *curator aquarum* must have been considerable. The total length of the aqueduct system was almost 500 kilometres, and the total labour force involved in the region of 700 slaves, overseers, reservoir-keepers, stonemasons, plasterers, miners and others. His duties included renovation of various parts of the system that had fallen into disrepair and maintenance. In addition, he had to get back a number of the workforce that had been taken off their proper work (due to bribes) and put onto odd jobs by private individuals (Landels, 2000). Frontinus tells us that he also made a map of the entire Roman aqueduct system, so that he could *"constantly have the whole network before his eyes and take decisions as if I was actually there on the spot."* Pliny has preserved for us a saying of Frontinus, which well applies to the man himself, *"Remembrance will endure if the life shall have merited it"* (9.19.1, 6).

There are problems when using Frontinus that must be born in mind. His statistics on water delivery are partial, dealing only with matters when he was in office. Sometimes his figures are inconsistent. These are serious considerations that make the task of researching the aqueducts all the more difficult. Another issue is that Frontinus is selective. While his stated objective is the aqueducts of Rome, he does not cover aspects of aqueducts that are found in other Roman aqueducts (Evans, 1997:53). For example, siphons.

Other authors

The aqueducts are mentioned by a number of authors, such as Dio Cassius, Martial and Suetonius, but usually only in passing. No technical details are ever mentioned, but the information is useful in determining the course, political or social details and sometimes construction details of the aqueducts.

Dio Cassius

Dio Cassius (c. AD 163 - c. 235) was a Roman historian born in Nicaea in Bithynia. He moved to Rome as a young man, and rose to the consulate under Septimius Severus. His work, the *Roman History*, was written in

Greek and consisted of 80 books. According to Dio Cassius, it took 22 years to research and write them. They are still partially extant. He is perhaps an underrated historian; his methods of research were meticulous and he typically rejected the fantastic. He was typically pragmatic (Speake, 1994:206). In many ways Dio Cassius calls to mind Thucydides.

Martial

Martial (c. AD 40 - 104) was a Roman poet, born in Bilbilis. He was a favourite amongst influential Romans. His most important work is the *epigrams* in 12 books. His contribution to the study of science and engineering in the ancient world is marginal (Speake, 1994:399).

Pliny the Elder

Pliny the Elder has an active public life in Rome, and was a close associate of Vespasian (Speake, 1994:504). His great curiosity resulted in a work entitled *Natural History.* This is a summary of the scientific knowledge of the early Empire. Though the book is marred by Pliny's credulity and the low level of science of the times, it is still a valuable work. Pliny's great curiosity killed him; he observed Vesuvius erupting and did not flee in time. He was clearly an admirer of the Roman aqueducts. To quote (*Nat. His.*, 36.123):

> *Now if someone shall carefully appraise the abundance of water in public buildings, baths, pools, channels, houses, gardens and suburban villas, the distance the water travels, the arches which have been built up, the mountains tunnelled, and the level courses across the valleys, he will acknowledge that nothing more marvellous has ever existed in the whole world.*

Pliny the Younger

Pliny the Younger's *Letters* provide a window into Roman life as seen through the eyes of a cultured gentleman of the Roman ruling class. His work provides minimal evidence, but should not be dismissed, as it provides useful corroborating evidence, and even at times revealing anecdotes which are recorded nowhere else. It is probable that his *Letters* was written for publication; perhaps he chose this format because his uncle had written so much on so many diverse topics (Speake, 1994:505).

Suetonius

Suetonius (c. AD 69 - c. 140) was a Roman biographer and a close friend of Pliny the Younger. Suetonius became Hadrian's chief secretary. While he had unparalleled access to people and sources, he seems to have concentrated on royal scandals (Speake, 1994:608). Unfortunately, the bulk of his output is lost, so we do not know if that was a characteristic of all of his work, or just that which we have.

3.3 Archaeological evidence

The archaeological evidence for the Roman aqueducts is, of course, the aqueducts themselves. However, unlike Pompeii, Rome has been continuously occupied since the construction of the aqueducts. Thus not only have the forces of nature taken their toll on the remains, but human activities too. The aqueducts have been plundered for building material, incorporated into other buildings, been covered over, been ploughed over and wantonly destroyed. In Evans' words, the archaeological evidence is scanty (Evans, 1997:135).

The result of this is that it is impossible to reconstruct the whole of the water system in Rome. All such efforts are at best educated guesses, with no sure means of testing for accuracy. However, it is possible to eliminate the impossible or extremely improbable, and thus narrow the range of possibilities.

As it is not always possible to examine the evidence first-hand, accounts in the secondary literature must be relied upon instead. This presents its own difficulties, as such accounts may be incomplete, may vary in quality, may rely upon supposition instead of observation, may focus on aspects not of relevance to this discussion and may contain faulty analysis.

However, there is some evidence that is only archaeological in nature. For example, there are considerable traces of activity on the four aqueducts from the Anio Valley, dated to the reigns of Hadrian and Septimius Severus. However, there is no literature or epigraphy that mentions the work of Hadrian, and only a single fragment of an inscription (*CIL* 6.1247) that vouches for the repairs on the Marcia by Septimius Severus (Ashby, 1935:14).

3.4 Numismatic evidence

There is very little numismatic evidence for the Roman aqueducts. Though aqueducts on coins don't provide much information, they are useful for dating purposes. However, there are a few coins of interest.

For example, one coin from 114/3 BC that has caused discussion has on it's obverse side the word ROM[A], which represents the head of a female referring to Roma or Venus behind the neck a star with six rays, the value sign for a denarius.[7] On the reverse side an equestrian statue is shown on a plateau supported by three arches isolated from its environment together with the capitals MN[MANIVS]. AEMILI. LEP, the name of the moneyer (See Figure D.6). In 1945 M. Stuart came to the conclusion that this image was related to the aqueduct Aqua Marcia. This interpretation is not completely accepted, though, as Crawford (1974:305) states, Stuart's arguments are stronger than the other arguments that have been put forward. According to Livius the construction of a new aqueduct was started in 179 BC under supervision of the censors M. Aemilius Lepidus and M. Fulvius

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[7] This coin is number 291 in Crawford (1974).

Nobilior. However, M. Licinius Crassus did not allow the aqueduct to cross his property, which halted the project. In the year 144 BC and with the help of a different M. Aemilius Lepidus, urban praetor Q. Marcius Rex received the order of the Senate to restore the Aqua Appia and the Aqua Anio Vetus and to build the third aqueduct. In 140 BC new objections were raised for aqueduct water to reach the Capitolinus without success: in the same year this new aqueduct, the Marcia, was put into use. This interpretation seemingly solves the problem of the relative short time of construction of an aqueduct of 92 km in length including 10 km on arcades. However, the arguments of this author were rejected by M.G. Morgan who concluded that the aqueduct line of 179 BC was never built (Kek, 1994:269).

Perhaps the most famous coin is the Marcia denarius, from 56 BC. On the obverse side the word ANCVS, possibly a reference to the fourth king of Rome, and on the reverse PHILIPPVS / AQUA MR can be seen.[8] See Figure D.8. The moneyer may be Q. Marcius Philippus, but opinion leans towards it being L. Marcius Philippus (Crawford, 1974:448). The moneyer honoured Q. Marcius Rex with this coin. The moneyer also belonged to the Marcia family.

One period where coins are especially useful is that antedating Frontinus. The aqueducts constructed after his time are poorly documented. For example, one useful sestertius, dating from Trajan's fifth consulship, dates the construction of the Aqua Traiani to perhaps 109 A.D. The coin reads on the obverse IMP CAES NERVAE TRAIANO AVG GER DAC P M TR P COS V PP. The text on the reverse reads SPQR OPTIMO PRINCIPI AQVA TRAIANA S C. with an image that can be interpreted in different ways: the genius of the aqueduct, an image of the castellum aquae (the water distribution station) at the end of this Roman aqueduct, or a collection of general elements of the water supply of Rome (See Figure D.9).

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[8] This coin is number 425 in Crawford (1974).

3.5 Epigraphic evidence

Inscriptions are an important source of information regarding the aqueducts of Rome. In lieu of examining the original inscriptions, *The Corpus Inscriptionum Latinarum (CIL)* is used, especially Volume 6. The most important inscriptions in Volume 6 are 1243 - 1268.

There are some limitations in using epigraphic evidence. One such limitation is that none of the inscriptions are earlier than the Augustan age (Sandys, 1927:129). Another is that inscriptions where not always intended to record fact; ancient politicians and emperors were well understood the value of propaganda.

We will now examine some of the important extant inscriptions.

Porta Praenestina

Above the rough stones of the arches of the Porta Praenestina, or Porta Maggiore, the smooth walls of the channels carries three inscriptions. The top inscription is bordered above and below by stone slabs that project from the roof and floor of the Anio Novus channel (Aicher, 1995:54). The inscription reads (*CIL 6.1256*):

> *TI. CLAUDIUS DRUSI F. CAISAR AUGUSTUS GERMANICUS PONTIF. MAXIM., | TRIBUNICIA POTESTATE XII, COS. V, IMPERATOR XXVII, PATER PATRIAE, | AQUAS CLAUDIAM EX FONTIBUS, QUI VOCABANTUR CAERULEUS ET CURTIUS A MILLIARIO XXXXV, | ITEM ANIENEM NOVAM A MILLIARIO LXII SUA IMPENSA IN URBEM PERDUCENDAS CURAVIT.*

This is a commemoration of the construction of the Claudia and Anio Novus, in 52 AD, by the emperor Claudius, "at his own expense". It states the sources for both, the former at the 45th milestone and the latter at the

62nd milestone. The second inscription is framed by horizontal mouldings that extend the floor and roof of the Claudia conduit. It reads (*CIL 6.1257*):

> *IMP. CAESAR VESPASIANUS AUGUST. PONTIF. MAX., TRIB. POT. II, IMP. VI, COS. III DESIG. IIII, P.P., | AQUAS CURTIAM ET CAERULEAM PERDUCTAS A DIVO CLAUDIO ET POSTEA INTERMISSAS DILAPSASQUE | PER ANNOS NOVEM SUA IMPENSA URBI RESTITUIT.*

This commemorates Vespasian repairing the Claudia in 71 AD. According to the inscription, the Claudia had been in ruins for nine years. Such a long interruption of the aqueduct after less than twenty years of use is a mystery. Perhaps the problem was upstream of the Claudia's junction with the Anio Novus channel, as the inscription does not mention repair of or damage to this aqueduct. The third and lowest inscription on the Porta Maggiore is framed in a space below the two channels, giving the false impression of a third channel below. The channel that can be seen there is in fact the Acqua Felice, built in the 16th century. The inscription reads (*CIL 6.1258*):

> *IMP. T. CAESAR DIVI F. VESPASIANUS AUGUSTUS PONTIFEX MAXIMUS, TRIBUNIC. | POTESTATE X, IMPERATOR XVII, PATER PATRIAE, CENSOR, COS. VIII | AQUAS CURTIUM ET CAERULEAM PERDUCTAS A DIVO CLAUDIO ET POSTEA | A DIVO VESPASIANO PATRE SUO URBI RESTITAS, CUM A CAPITE AQUARUM A SOLO VETUSTATE DILAPSAE ESSENT, NOVA FORMA REDUCENDAS SUA IMPENSA CURAVIT*

This was erected in honour of Titus restoring the Claudia in 81 AD, after the aqueduct was "ruined to its foundations from age". The fact that such restoration was required only a decade after the first repair raises questions about the quality of the initial construction.

Porta Tiburtina

The Porta Tiburtina was originally a monumental aqueduct crossing. Later it was made into a gate in the Aurelian Wall. The partitioning of the three channels above the arch is very similar in design to Porta Maggiore. The travertine facing of the middle channel shows the traces that the moulding of this original archway formed a pediment here. Caracalla chiselled this off for an inscription recording his restoration of the Marcia in 212 AD. There are, like the Porta Maggiore, three inscriptions of interest here. The first (*CIL 6.1244*):

> *IMP. CAESAR DIVI IULI F. AUGUSTUS | PONTIFEX MAXIMUS COS. XII | TRIBUNIC. POTESTAT. XIX IMP. XIIII | RIVOS AQUARUM OMNIUM REFECIT.*

This commemorates the restoration of the Marcia, Tepula and Julia by Augustus between 11 and 5 BC. The middle inscription, Caracalla's, is (*CIL 6.1245*):

> *IMP. CAES. M. AURELLIUS ANTONINUS PIUS FELIX AUG. PARTH. MAX. | BRIT. MAXIMUS PONTIFEX MAXIMUS | AQUAM MARCIAM VARIIS KASIBUS IMPEDITAM, PURGATO FONTE, EXCISIS ET PERFORATIS | MONTIBUS, RESTITUTA FORMA, ADQUISITO ETIAM FONTE NOVO ANTONINIANO, | IN SACREM URBEM SUAM PERDUCENDAM CURAVIT.*

This refers to Caracalla's restoration work of 212 AD, which seems to have been quite extensive. It involved new arcades and tunnels, and the addition of a new source for the Marcia (the fons Antoninianus). The lowest inscription is (*CIL 6.1246*):

> *IMP. TITUS CAESAR DIVI F. VESPASIANUS AUG. PONTIF. MAX. | TRIBUNICIAE POTESTAT. IX IMP. XV CENS.*

> *COS. VII DESIG. IIX P.P. | RIVOM AQUAE MARCIAE VETUSTATE DILAPSUM REFECIT | ET AQUAM QUAEIN USU ESE DESIERAT REDUXIT.*

This commemorates Titus earlier restoration of the Marcia, in 79 AD.

Aqua Traiani

Another important inscription is to be found in *CIL* 6.1260, which dates the construction of the Aqua Traiani to 109 A.D. This is particularly useful, as we have little documentary evidence for the Traiani.

> *AES[A] | [N]ERVAE . F . N[ERVA] | [T]RAIANVS . A[UG] | GERM . DACIC | [PO]NT . MAX. TR. POT. XI[II] | IMP . VI . COS . V . P .P | AQVAM . TRAIANAM | PECVNIA . SVA | IN VRBEM . PERDVXIT | EMPTIS . LOCIS | PER . LATITVD . P . XXX .*

Miscellaneous inscriptions

CIL 1.808 is a valuable inscription that gives insight into the cost of construction in republican Rome.

> *OPERA . L[OC] | IA . CAECILIA DE . H | D . MIL . XXXV . PONTEM . IN . FLVIO | A . AD . TRIBVTA . EST . POPVLO . CONST | Q . PAMPHILO . MANCVPI . ET OPE | [V]IAR . T . VIBIO . TEMVVDINO . Q . VRB | REA STERNENDA . AF . MIL | [P]ENNINVM . MVVNIE[N] | XX PECUNIA . AD . TRIB[VTA] | ONST HS N[] . L[] RVFILIO L . L .I | [S]TI MANCUPI CVR . VIAR . T . T . VIP | [M]IL . LXX[]III . AD MIL . CX | LA INTERAMNIVM . V[O] | XX . PECVNIA . AD. TRI | LO . CONST . HS [] | T . SEPVNIO . T . F . O | R . T VIBIO / - M | ARCVS DE LA | MANCVPI | Q VRB*

Evidence for a number of items exists only in the epigraphic evidence. For example, *CIL* 15.7259 provides the only evidence for the existence of the *Aqua Pinciana*.

AQUA PINCIANA | D N FL VALENTINIA | NI AVG

CIL 6.33087 provides the only evidence for the existence of the *Aqua Conclusa*.

> *Q . POMPEIVS BITHYNICI . L . SOSVS | SATRIENA . P . L . SALVIA . VXSOR . FRVG | OPSEQVENTES . ET . CONCORDES . ESQVILEIS . AB . AQUA | CONCLVSA . FECER . SIREI ET . SVEIS . ET DIGNEIS | DVM . SVPPEDITAT . VITA . INTER NOS . ANNOS . LX . VIXIM VS . CONCORDES | MORTE . OBITA . VT . MONVMENT[]VM . HABEREMVS . FECIMVS . VIVI | STVDIUM . ET . ACME . L . VT . VNA . CONDEREMVS . CONDITIVOM | CVBICVLVM . FECERVNT*

There are a number of inscriptions that link particular individuals to the aqueducts. Unfortunately, these inscriptions provide little information about the aqueducts themselves. An example of this kind of inscription is *CIL* 6.2344. This is a funerary monument set up by a public slave called Soter, and L. Calpurnius Flavianus, whose status is not made explicit. They dedicate the monument for their family, themselves and for their descendants.

Soter is specifically referred to as a public slave. As a *castellarius*, he would have been in charge of the *castella* of the Anio Vetus.

> *D . M | SOTER . SERVOS . PVBLICVS | CASTELLAR . AQVAE . ANNIONIS | VETERIS . FECIT . CONIVGI . BENE | MERENTI . ET . L . CALPVRNIVS | FLAVIANVS . MATRI*

> *. BENE | MERENTI . SIBI . ET . SVIS | POSTERISQVE . EORUM*

An example of a *cippus* is provided by *CIL* 6.1250c.

> *MAR | IMP . CAESAR | DIVI . F . AVGVSTVS | EX . S . C | C* ∞ *. P CCXI*

3.6 Conclusion

The sources are scanty; much has been lost and much that still exists is inaccessible. Many sources are unreliable due to conflicts between the original purpose and the purpose we put them to. Some sources are unidentified, some misidentified. Some are enigmatic and open to multiple valid interpretations. However, by systematic examination of the evidence, beginning with the actual material remains of the aqueducts (or records thereof), and then placing in the proper order the epigraphic, numismatic, topographical, geographic and written sources, an acceptably accurate picture of the Roman aqueducts can be drawn.

Chapter 4

TOOLS, SKILLS AND CONSTRUCTION

4.1 Introduction

The nature of Roman tools can be determined both from carved representations of artisans at work, and from actual artefacts that have been preserved to this day (O'Conner, 1993:45). While examples of the hammer, anvil, axe, adze, pick, knife, scythe, spokeshave, plane, chisel, drill, *chorabates*, *dioptra* and file have been found, it is certain that some tools and techniques have been lost.

4.2 Levels

Roman architects were skilled in this kind of work, for which they used sophisticated tools. Besides the ordinary level, similar to the one used today by carpenters, they used devices such as the *chorobates* and *dioptra*.

The *chorobates* was a bench with weighted strings on its sides for measuring the ground's angle on a system of notches, and a short channel in the centre, likely for testing the direction of the water flow (O'Conner, 1993: 45). It was mostly used for the levelling of aqueducts. It was probably too unwieldy for general levelling (Dilke 1971:76). It was also probably too unwieldy to use in the construction of tunnels, being too big to manoeuvre easily in confined spaces. See Figure D.15 for an illustration of a *chorobates.*

The *dioptra* was a different kind of level. It rested on the ground, and was finely adjusted by tilting and rotating the top part by means of precision screws, it could assess the angle of a stretch of aqueduct by looking through pivoting sights (O'Conner 1993:45). See Figure D.16 for an illustration of a *dioptra.* Whether or not it was actually used is debatable, as only Hero of Alexandria[1] gives us a description of the device. Vitruvius recommends the *dioptra* as an alternative for levelling water-courses and Pliny the Elder recognised its efficiency for astronomical work. Vitruvius' reservations and the lack of further written evidence suggests that it may have been regarded as too elaborate, expensive and unwieldy for general use (Dilke, 1971:79). As Hauck (1988:44) points out, the *dioptra* was essentially a forerunner of the modern theodolite. Despite its apparent complexity, it would have been useful in tunnels where the *chorobates* could not be used.

However, a reading of Vitruvius leaves the impression that the *dioptra* may have been the first choice in some cases. While his reliability has been questioned, it seems a stretch that that he would not have knowledge of what would be a common tool. In Vitruvius' own words (8.5.1):

> *The first stage is to fix levels. This is done by dioptrae, or water levels, or the chorobates. But the more accurate method is by the chorobates because the dioptrae and he water levels mislead.*

If the *chorobates* is superior, why would the other devices be used? Vitruvius provides the answer; wind can disturb the plummets on the *chorobates* (8.5.2), a problem to which the *dioptra* and water levels would have been immune.

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[1] During Nero's reign

The principal Roman surveying instrument was the *groma* (See Figure D.17). It was regarded as the tool most typical of a surveyor; it appeared in stylised form on the tomb of Lucius Aebutius Faustus.[2] The *groma* was used in military and civilian surveying, and we are told that a central point in a military camp was called the *gromae locus* (Dilke, 1971:66). Since no *groma* has survived completely intact, we do not have an accurate picture of one. The one that appears on Lucius Aebutius Faustus' tomb serves as a starting point (see Figure D.18). The staff of the surveying instrument is upright and the cross is detached and laid diagonally across it. There is not enough evidence to say for certain that this instrument is a *groma*, but the consensus is that it most likely is (Dilke, 1971:66). It certainly matches the description.

During excavations in Pompeii in 1912, some metal parts were found in Verus the surveyor's workshop that might be the remains of a *groma*. Matteo Della Corte created a plausible reconstruction from these remains. At the top is the cross, which has iron sheeting and originally enclosed wooden arms. To prevent inaccuracy due to the wearing away of the wood, the arms were reinforced near the centre by bronze angle-brackets. A plumb-line hung through a hole near the end of each arm. The four plumb-bobs were not identical, but came in two pairs arranged at opposite corners. The system of sighting from one plummet to its opposite number worked most effectively when the cross was off-centre, otherwise there would be an obstruction. The cross was thus placed on a bracket and not directly on the staff. The bottom of the bracket fitted into a bronze collar set into the top of wooden staff. The horizontal distance of the centre of the cross from the staff was 23.5cm. The staff may have been as long as 2m (Dilke, 1971:70).

The method of operation of the *groma* was for the surveyor to plant it in the ground a bracket length away from the required centre of survey. It was

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[2] L. Aebutius Faustus lived in the colony of Eporedia in northern Italy. He was a freedman (Hauck, 1988:42)

then turned until it faced the required direction. Sighting was accomplished by looking from one plummet to its opposite number. Sights could be set on to a second *groma*, positioned perhaps one *actus*[3] away, then a similar distance from the first and second *gromae* at right angles. The square would then be complete and cross-checks made. As can be seen, the *groma* had only limited use. It enabled straight lines, squares and rectangles to be surveyed. These were exactly what the *agrimensor* required, so more complicated equipment was not needed. If there was not much wind, the *groma* would work adequately. In the case of too much wind, a wind-break could be constructed, or the surveyor could wait for favourable weather (Dilke, 1971:70). If as tall as 2m, its use in tunnels would have been restricted. However, a shorter *groma* would have been ideal for this purpose.

A portable sundial was also found in Verus' workshop in Pompeii. Not only was this intended to indicate time, but lines on two of the sides were used for measurements. The exact use of the sundial is uncertain. A sundial can be used for more than tracking time, it can also be used to orientate buildings (Dilke, 1971:72).

Another levelling instrument used by the Romans was the simple *libella.* It consisted of a frame in the shape of the letter A, with the addition of a horizontal bar on top. From the apex a plumbline was suspended that coincided with a mark on the lower crossbar when the instrument was level. Other marks could have been added to indicate other slopes, but there is no evidence that this was done (Hauck, 1988:43).

The horizontal accuracy of the aqueducts speaks of the quality of the tools and skill of the Roman engineers. The tools, however, seemed less accurate when used for turning angles. For example, when building an aqueduct at Saldae a tunnel had to be dug through a mountain. The Romans had teams digging on each side of the mountain, but when each half of the

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[3] Approximately 35.48 m.

tunnel exceeded half the thickness of the mountain, they realised they had a problem. The engineer Nonius Datus[4] was summoned, and he discovered that both teams had veered to the right and missed each other. The error was lateral and not vertical, probably the more common of the two possible errors[5].

4.3 Lifting apparatus

The five powers of Hero (*c.* A.D. 62) were the windlass, level, pulley, wedge and screw. According to O'Conner (1993:47), to this list should be added the roller, wheel, axle and the gear or toothed wheel. The oldest are the wedge, roller, wheel and the axle. The wheel and axle is believed to have been in use by 3000 B.C., and the wedge and roller some time before that. By 2000 B.C. the Egyptians where using levels, sledges, rockers and rollers in quarrying. They also used a windlass that applied tension by the twisting of multiple sets of ropes (O'Conner 1993:47).

A windlass is a lifting device. It consists of a drum on a horizontal axle which is anchored against displacement. A rope from the drum is tensioned by rotating the drum using some form of grip like handspike or lever. This type of windlass, as well as the pulley, was known to Aristotle. The screw is usually attributed to Archimedes, but may have actually been invented earlier by Archytas of Tarentum (O'Conner 1993:47). The Romans made cranes that made use of the windlass to lift heavy objects (Landels, 2000:85).

The most primitive gear is the toothed wheel. This was used, for example, by the Egyptians for lifting water by transforming rotation about a vertical axis to rotation about horizontal axis. It has been attributed to Archimedes. There is some evidence for this, it certainly appeared at about his time.

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[4] Nonius Datus was robbed and wounded by bandits on the way to Saldae. In compensation for his perseverance and skill, he was awarded with a monument at Lambaesis.

[5] Also the easiest to correct.

It is unclear if the Romans used toothed gears in the construction of the aqueducts, but one can speculate that they may have been components of other machines. A modified toothed wheel, called a ratchet, was probably used to ensure movement in only one direction (Landels, 2000:11).

More complex gear systems are discussed by Hero and Aristotle. In Problem 11 of his *Mechanical Problems* Aristotle describes the roller.

> *... on the rollers there is no friction at all, but on the carts there is the axle, where there is friction... The burden upon the rollers is moved on two points, the ground supporting from below and the burden lying above, for the circle turns at both these points and is pushed forward the way it travels.*

In Roman aqueduct construction one of the most pressing problems was to move heavy weights, especially in the construction of temples, bridges and tall buildings. A stone block, for example, would have to be moved on the quarry floor, lifted, carried to the building site and then placed in position (O'Conner 1993:48). There is no doubt a variety of tools would have been used for this purpose, from the lever to sophisticated cranes. We have many references to cranes in the literature, but actual physical remains are almost completely lacking. However, the evidence of their existence is in the form of tall structures that could not have been constructed without them (Landels, 2000:84). It is almost certain that wood would have been used in their construction, and wood only survives a period of 1800 years or more under extraordinary circumstances.

The principle of the lever was well understood, and written about by Hero and Aristotle in *Mechanica* and *Mechanical Problems* respectively. It is clear the Romans understood that that longer the lever between mover and fulcrum, the greater the force exerted on the load. They also seemed to understand that the weight of the load and the force needed to lift it are inversely proportional to their distances from the fulcrum (Landels, 2000:195).

From the evidence, one can deduce that the Romans had a knowledge of the three orders of lever, even if they did not call them that.

The Romans used a device called a *tympanum* to lift water (see Vitruvius 10.4). It consisted of a large wheel, perhaps 1.5m in diameter, with several internal sectional chambers. The chamber at any any one time and takes in water through an opening in the rim. As the wheel turns the water is drained through the hollow axle of the wheel. Thus water is raised by about half the diameter of the *tympanum* (Landels, 2000:63). Vitruvius (10:15) tells us the following of its capacity:

> *Now this [the tympanum] does not lift water to a great height, but draws a large amount in a short time.*

Vitruvius then tells us of a similar device, with buckets fixed around the circumference of a wheel, which could lift water the full diameter of the wheel. A more efficient device than the *tympanum* was the *cochlea*, or Archimedean screw. Using this, water is raised by a spiral turning inside a tube. There was a pump, described by Vitruvius (10:17), invented by Ctesiphon and called a *Ctesibica machina* (Hauck, 1988:50). The pump could, according to Vitruvius, raise water to a great height. This device is cleverly conceived and requires a high degree of skill to construct. It is best described by Vitruvius himself (10.7.1):

> *It is to be made of bronze. The lower part consists of two similar cylinders at a small distance apart, with outlet pipes. These pipes converge like the prongs of a fork, and meet in a vessel placed in the middle. In this vessel valves are to be accurately fitted above the top openings of the pipes. And the valves by closing the mouths of the pipes retain what has been forced by air into the vessel. Above the vessel, a cover like an inverted funnel is fitted and attached, by a pin well wedged, so that the force of the incoming water may not cause the cover to rise. On the*

> *cover of the pip, which is called a trumpet, is jointed to it, and made vertical. The cylinders have, below the lower mouths of the pipes, valves inserted above the openings in their bases. Pistons are now inserted from above rounded on the lathe, and well oiled. Being thus enclosed in the cylinders, they are worked with piston rods and levers. The air and water in the cylinders, since the valves close the lower openings, the pistons drive onwards. By such inflation and the consequent pressure they force the water through the orifices of the pipes into the vessel. The funnel receives water and forces it out by pneumatic pressure through a pipe. A reservoir is provided, and in this way water is supplied from below for fountains.*

The existence of such a device provides more evidence for the high level of Roman skill. Moreover, it provides solutions to the problems of water distribution within Rome and to diverting modest amounts of water during maintenance. One can also speculate that water lifted in such a fashion could be used to test raised sections of the aqueduct before the whole was completed; to discover a leak after the entire aqueduct was complete and water from the source was running through it would have complicated matters. It is unlikely these were used as part of the aqueduct system on a daily basis, but rather for special purposes as outlined above.

4.4 Construction

Construction of roads, bridges and aqueducts required four elements: higher authorities to make the initial decisions, technical experts to put the decisions into practice, the correct materials and labourers to do the actual work. Decision making, planning, construction, obtaining and fashioning the materials each required different and sometimes specialised skills. It is easy to dismiss technical skill for the first of the elements as unlikely in this day of managerial theory, however the Roman system did not permit an individual to reach the highest ranks without training and experience[6]. As early as the 4th century BC the positions of public office had been arranged into an orderly progression known as the *cursus honorum.* The normal course began with a period of military service, then a *quaestorship* or more probably a series of appointments such as *aedile*, *praetor* and possibly even *consul*, followed by *censor* and in some cases *dictator*. By 180 BC minimum ages had, rather sensibly, been set for higher positions. We also have evidence that at least two higher officials had technical skill, Marcus Vipsanius Agrippa[7] and Sextus Julius Frontinus (O'Conner, 1993:36). Both had marked influence in the construction and administration of aqueducts in their time, and appeared to be men of high competence and energy. In the opinion of Hauck (1988:46) the Roman engineers had no formal understanding of force vectors and their resolution, shear and bending moment, the nature of stress, tension or compression, and other basic engineering principles. Probably then, their knowledge was developed empirically. Strong intuition and experience must have played a role.

Most ancient aqueducts were gravity systems. That is to say that they did not employ any means of pumping or moving water besides that of gravity in the aqueduct system, except perhaps for testing and water diversion during maintenance. By ensuring the source was higher than the termination, and by plotting a course for the aqueduct which maintained a uniform downward gradient, the water would flow purely by gravity. This required a detailed knowledge of the terrain. Engineers had to maintain a uniform slope while bridging valleys and tunnelling through hills. This required skilled surveying and the construction of detailed maps (Heiken, Funiciello & De Rita, 2005:143). This provides evidence for the high level of Roman planning. Possessing the skill is a necessary skill, but without a method of planning and control, the aqueducts could not be built.

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[6] Something that many in the modern world lack.

[7] to whom Augustus granted many well-deserved honours for his remarkably varied accomplishments

For most of their length the aqueducts were simply channels (*rivus* or *specus*) or tunnels, or less commonly pipes. The depth of the channel below ground varied so as to maintain a constant, shallow gradient throughout the length of the aqueduct. Vertical shafts were bored at intervals to provide ventilation and access. Only in the final stretches were aqueducts raised on arches, to give sufficient head for distributing water in the city. In order to maintain the shallow gradient the aqueducts did not take the most direct route to Rome, but followed the contours of the land and heading along spurs that led towards Rome. Tunnels were only resorted to when the fall from source to termination was too slight for a longer circuit around an obstruction, like a hill or mountain. In time, Roman engineers became more daring in the construction of high arches to support the conduits across valleys and plains. Some of the later aqueducts were as much as 27 metres off ground level. Closed pipes were occasionally used to span valleys using the inverted siphon method. Pressure forced the water down and up again on the other side of the valley, but to a slightly lower level than before. This system was costly as it required lead pipes and it was difficult to make joints strong enough to withstand the considerable pressure exerted by the water.

Herodotus gives us a clear Greek precedent for the Roman techniques in the astonishing aqueduct built at Samos by the Megarian named Eupalinus, at the order of Polycrates. Herodotus describes it thus (3.60):

> *... a tunnel nearly a mile long, eight feet wide and eight feet high, driven clean through the base of a hill nine hundred feet in height. The whole length of it carries a second cutting thirty feet deep and three broad, along which water from an abundant source is led through pipes into the town.*

The Samos aqueduct is 1036 metres long, approximately 2.4 metres square. It was dug from two openings, with the two working groups meeting in the centre of the channel. The construction started in 530 BC and took about ten years. The error was only 60 cm. The workers faced problems with the unstable soil and had to deviate from the original course; they still managed to determine the correct path to the opposite working team. The deviation was 200 metres away from a straight line connecting the ends of the tunnel. Around 7000 cubic meter rock were removed from the mountain. Using the text of Herodotus, Guerin (1856) uncovered the entrance of the aqueduct. Between 1971 and 1973 the German Archaeological Institute of Athens uncovered the entire tunnel (Kienast, 1977 & Tsimpourakis, 1997).

The typical Roman aqueduct was a surface channel in that it followed the surface of the land, instead of being raised on arches or sunk beneath it in a tunnel (Hodge, 2002:93). The channel was usually fifty centimetres to one metre below the ground, deep enough to afford some protection but shallow enough to provide access when repairs were required. Vitruvius specifies three types of conduit, namely masonry channels, lead pipes and terracotta pipes. By far the most common channel was masonry. The channel was built using the ”cut and cover” principle rather than directly tunnelling it. Essentially, a hole was dug, the channel constructed, and then covered. This is quicker, easier and cheaper than tunnelling. In cross-section, the conduit normally formed an oblong, taller than it was wide. The size of the conduit varied, but the Marcia (90 cm wide by 2.4 m high) and the Brevenne (79 cm wide by 1.69 m high) give an idea of the averages. A vault usually formed the roof. Less commonly a pair of tilted flat slabs where used to form a pointed roof. The reason for these proportions is practical. The channel had to be accessible to a man for maintenance and cleaning, and it was this factor and not the volume of water to be carried that governed its size (Hodge, 2002:94). The channel was normally only one half to two-thirds full of water anyway, and was never intended to carry more. The floors and walls were lined with waterproof cement. The cement was usually not all the way to the roof, but only as high as the water would actually rise. The function of the cement was threefold, to make the channels impervious to leaks or seepage, to provide a smooth, friction-free contact surface and to make the contact surface continuous and uniform with no joints from one end of the aqueduct to the other. As well as performing these functions, the cement had to be strong and resistant to cracking, whether from heat expansion, freezing or other causes. The cement also had to be able to cure while wet. The cement was typically installed in layers, and the last layer was polished. There were three reasons for polishing the cement. Firstly, to inhibit the formation of lime deposits and to make the removal of such deposits easier. Secondly, to harden the top layer and thus protect the other layers. Thirdly, to process the particles of lime and marble to form a horizontal orientation which prevents cracking due to shrinkage. Both the composition and the installation were therefore very complex tasks, the ingenuity of which must not be underestimated (Hodge, 2002:98).

The gradient of the aqueduct was an important factor. Too shallow a gradient and the water would not move, and to steep a gradient means the water would move too quickly. Typically, the slower the current the less need there would be for repairs, but the more time there would be for sediment in suspension to settle and clog the channel. A faster current would keep the channel cleaner, but would necessitate more repairs. The gradient was not uniform for an entire aqueduct, for a number of reasons. A tunnel might have a steeper gradient than average for the entire aqueduct, to keep it cleaner in view of the difficulties of cleaning it. A tunnel is also less likely to require repairs than a channel. A rapid increase in gradient might also serve to slow water down. The rate of flow increases, but the forward momentum does not increase. Like a waterfall, the turbulence at the end of the slope serves to slow the water down (Hodge, 2002). The ancient sources give two quite different figures for a minimal acceptable slope, and these are not uncommonly at odds with the gradient of a number of aqueducts. Vitruvius suggests 0.5% and Pliny specifies 0.02%. The aqueducts themselves range between 0.3% and 0.15%, with extremes of 0.07% and 3.0% at Nmes and Rome respectively (see Hodge, 2002:178).

The length of the aqueducts was expressed in *passus* ("steps"), a common Roman measurement. A *passus* corresponded to 1.482 m or 4 ft 10 $\frac{1}{4}$ in. The next order of magnitude was the *milia passus*, or Roman mile. This actually meant "thousands of steps". A *milia passus* equals 1.482 km, or 0.92 mi. The Romans also used the *pes*, or foot, a measurement they inherited. The *pes* varied through time from 295.7mm to 297.3mm. The 1/12 part of a *pes* was called *uncia*, 1/16 was called *digitus* and the 1/4 part *palma*. Five *pedes* made a *passus*, the standard double step of a soldier. To measure land surveyors used the *actus*, equal to 120 *pedes* or 24 *passus*. Two square actus made an *iugerum* (Hauck, 1988:36).

4.5 Cost

Originally, the money for the aqueducts came primarily from war-booty and from the patronage of wealthy individuals. Many of these would have made their fortune in war, or inherited it from an ancestor who did. The state also had income from the taxes imposed on conquered people, but this would become a more important source of funds during the empire. The sudden income from pillage was ideal to meet the outlay of money needed for aqueduct construction. Rome itself benefited most from this income. The aqueducts, and many other services, were never expected to pay for themselves, but were supplied to the people as a benefit (Aicher, 1995:26).

The construction of the aqueducts caused a number of changes in the way the Republic's finances functioned. Erdkamp, in Rosenstein & Morstein-Marx (2006:284), states that the first issues of silver coins by Rome were minted in Campania around 310 BC. They were probably issued to pay for the construction of the Via Appia, but might also have been minted to pay for the Aqua Appia. Also, the Anio Vetus was paid for by the spoils of the Pyrrhic War, and was one of the earliest examples of a system of public finance which deliberately embellished the Roman state by means of war-booty (Ashby, 1935:41). This method of finance remained more-or-less intact for the duration of the Republic. Under the Empire, the Emperor took over responsibility for public works. At that time, private donations and taxation were also used to finance the construction. However, such a large drain on state and private purses without return on capital surely drained the wealth of the state and people of Rome.

Vitruvius' model for an aqueduct had private customers paying their water. This was actually the case in most towns. Rome was different. In Republican times the private use of aqueduct water was not prevalent. Only the overflow water was sold to private users. With the construction of new aqueducts in Imperial times, more water become available for private users. Much of this water was free, available in grants bestowed by the emperor. He would determine the amount[8], and send a letter of authorisation to the curator. The curator would give the job of installation to the procurator and his men. The grant was given to an individual, not to property, and it was not hereditary. If the individual died or the property was sold the water reverted to imperial discretion. Sometimes the *aquarii* sold the water in the interim for their own profit (Aicher, 1995:26). Some users continued to pay in Imperial times as they has in Republican. Frontinus records a yearly income of 250,000 sesterces from the sale of aqueduct water. He does not identify who these users are.

Pipe inscriptions reveal that about half of the private users who were granted water belonged to the numerically fewer senatorial class. That these were precisely the people who could afford most to buy it is a standard feature of Roman patronage (Aicher, 1995:27).

According to Frontinus the money allocated for public works, including the Aqua Marcia, was 180 million sesterces[9]. According to Frontinus,*the term of his praetorship was not sufficient for the completion of the enter-*

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[8] One of the standard calix sizes

[9] This may have been equal to four and a half years revenue (Evans, 2000:84)

prise.. As the Marcia is 91km, the cost was approximately two million sesterces per kilometre. Leveau (1991) estimates that it cost between one and three million sesterces per kilometre on average to build an aqueduct. Hauck (1988:153) estimated that the aqueduct of Nemausus (including the Pont du Gard) cost two million sesterces per kilometre. At approximately 50km, that would have cost in the region of 100 million sesterces. Thus, modern estimates seem to accord well with Frontinus' reported budget for the Marcia. However, Frontinus states that the *Aqua Claudia* and *Anio Novus* to have cost only 55.5 million sesterces. As the Claudia was out of operation within less than two decades of its construction, this may indicate that poor materials and workmen were used.

The cost, and duration, of the work was a function of the difficulties, i.e. tunnels, bridges, arcades, raised foundations, siphons, cascades, ground composition and so on. If Frontinus' figures can be relied upon, then the Marcia cost 1.966 million sesterces per kilometre, and the Claudia and Anio Novus 2.248 million sesterces per kilometre.

CIL 1.808 (see Chapter 3.5) provides an idea as to the cost of building in Rome early in the last century of the Republic. Paving twenty miles of the Appenine road, starting with the 78th milestone, with gravel cost 150,000 sesterces. Another unknown length, but at least thirteen miles, cost 600,000 sesterces. Pliny (33.17), in his *Natural History*, tells us that at the beginning of the social war there was 1,620,831 sesterces in the public treasury. Caesar withdrew from the treasury 15,000 pounds of gold, 30,000 pounds of silver and 30,000,000 sesterces. We can see that the size of the public treasury could vary enormously, and one is lead to suspect that no exact figures have come down to us[10]. We can conclude that the cost of construction and maintenance was high, considering the relatively high costs of maintaining short sections of roads.

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[10] If they ever existed

4.6 Labour

Historians are not sure how major public projects were completed in Rome (Flower, 2004:174). Chanson (1999) and Hodge (2002:191) states that the majority of the labour was undertaken by the army; however. Private and public slaves and forced labour also played its part in the construction of roads, harbours and other public buildings (Flower, 2004:174).

There is also some direct evidence of public contracting with citizens.[11] The *lex parieti faciundo* is a detailed document from 105 BC drafted by local *duumviri* that describes the job of building a wall. Potential contractors, known as *redemptores*, were required to provide sureties in the form of people, known as *praedes*, and landed property, or *praedia*. The *redemptores* had to respect set dimensions and quality standards in terms of the construction materials they employed. The work was to be completed to the satisfaction of the *duumviri* and a council attended by at least twenty former *duumviri*. Payment was made in two instalments, half at the time of contracting and half at the time of approval (Flower, 2004:174).

A great deal of Roman building construction was based on the principle of mass production by semi-skilled labour. This would have lent itself to modular design, the repeated construction of identical elements, such as arches and columns (Hodge, 2000:164). This simplified the Roman building process, and allowed the system to perpetuate itself without extensive education of the labourers and administrators. It also had the beneficial consequence of providing work for a large number of people, who may otherwise have turned their attentions to antisocial behaviour.

As Roman labour was probably relatively unproductive on the average (Hodge, 2002:128), the cost of building aqueducts may have been more expensive than they should have been. However, this may not have been a

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[11] From the Roman colony of *Puteoli*.

serious issue. The construction of the aqueducts would have increased the food supply in the areas surrounding them by providing more water for irrigation.[12] The majority of the labourers would have been in the field with a ready supply of water. Keeping so many occupied in construction for so long and then having so many enjoy the fruits of the labour in the form of increased production of food, potable water and entertainment, will have outweighed the inefficiencies in the system. There is some evidence that Vespasian, at least, recognised the political necessity of keeping people occupied. In his *Life of Vespasian*, Suetonius writes (18):

> *To an engineer who promised to transport some heavy columns to the Capitoline Hill at a low cost, he gave a significant reward for his scheme, but refused to put it into operation, saying "You must let me feed the poor folk".*

4.7 Locating the source

The source of clean, constant and copious water was not always obvious. The search for it turned into an empirical science. When the source was obvious, like springs, streams or lakes, the engineer had only to determine the quality of the water. Vitruvius tells the engineer to not only test the clarity, taste and flow of the water, but the physique and complexion of the locals who drink it. Soil and rock types are also good indicators. Clay is generally a poor source, but water found around red tufa will be copious and pure. In Vitruvius' (8.1.2) words:

> *In clay the supply is thin and scanty and near the surface; this will not be of the best flavour. In loose gravel the supply is scanty but it is found lower down; this water will be muddy and unpleasant. In black earth, moisture and small drops are found; when*

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[12] It is not certain if aqueduct water was used for farm irrigation in Rome, though it is likely that it was, even if not officially. Increased drinking water would have increased productivity anyway.

> *these gather after the winter rains and settle in hard solid receptacles, they have an excellent flavour. But in gravel small and uncertain currents are found; these also are of unusual sweetness. In coarse gravel, common sand and red sand, the supply is more certain, and this is of good flavour. The waters from red rock are copious and good, if they do not disperse through the interstices and melt away. At the foot of the mountains and in flinty rocks water flows more copiously; and this is more cool and wholesome. Springs on level ground are salt, coarse, lukewarm and unpleasant, unless they flow from the mountains underground, and break out in the middle of the fields, and there under the shadows of the trees they furnish the sweetness of mountain springs.*

Many springs were underground and had to be found. That this could present problems is clear from the stories of the discovery and naming of the Aqua Virgo. According to the story, a local girl pointed out the underground springs to Agrippa's military engineers. This story is preserved in the Trevi Fountain. Vitruvius advises engineers in search of underground water to examine soil type, surface vegetation and landscape formations. The presence of water-loving plants like willows, alders and rushes on higher-lying ground is a good sign that water lies below them. Morning mist on the landscape can indicate a source, as can bright green grass in a dry season.

Once found, the water had to be channelled. Some areas were too swampy for construction and some water too foul for consumption. A good source of water is a natural limitation on the number of aqueducts that supply a city.

4.8 Surveying the course

The Romans attributed great antiquity to land surveying. Indeed, there is some evidence of Etruscan roots in the Roman methods and religious rites. The Romans insisted in setting the *groma* with correct auspices. The whole notion of boundaries and boundary marks had religious significance to the Romans. Rome was also indebted to Greece and Carthage, though it is unlikely they would admit to the latter (Dilke, 1971:31). The Roman system of education was not very technical. Nonetheless, surveyors had an adequate grounding in geometry, orientation, sighting and levelling, distance calculations, astronomy and cosmology and perhaps a little law. The latter was probably limited to the law governing the classification of land and those concerning boundaries and boundary disputes (Dilke, 1971:47). These traditional surveying skills would have been directly applicable to planning and surveying the aqueducts' courses.

Since the aqueducts were operated by gravity (see chapter 4.4), the course of the channel had to be carefully planned so that it would maintain a steady slope. A steep gradient was avoided, since faster flowing water would erode the channel walls and threaten the stability of the structure, especially at bends. These constraints would have affected possible courses the aqueducts took. Vitruvius gives a figure of 0.5% as an ideal angle of descent, but in practice this varied considerably, the average gradient usually lying between 0.15% and 0.3%, due to the constraints of geography. The Aqueducts of Rome were typically closer to the higher number; the terrain is quite hilly. The skills needed to level must have been in regular use too; it is unlikely that the Romans rediscovered them every time they built an aqueduct.

Vitruvius recommends the *chorobates* as the most accurate surveying instrument. In tunnels where it would be impractical, a simple water level could be used. Since the tunnels were connected to the surface with vertical shafts at frequent intervals, it was generally not difficult to keep the tunnel straight (Aicher, 1995:8). A plumb line could measure both the depth of the tunnel below the surface and ensure that the shaft descended vertically.

4.9 Construction materials

An engineer or artisan must work within the constraints imposed by his materials and skills; these limit his ability to shape, transport and handle materials and finished goods. The growth and stability of Rome was in large part due to the richness of its site and the neighbourhood in a variety of excellent building materials that were available to Roman engineers and artisans. The material varied in quality and over time.

4.9.1 Stone, brick and tile

Building stone was quarried as early as 2800 BC The Egyptians quarried soft rocks like limestone, but they also managed harder materials like sandstone, serpentine, basalt and granite (O'Conner, 1993:51). This was accomplished with wood, stone and bronze tools. O'Conner (1993:51) mentions the Egyptians were able to saw limestone using copper blades fed with sand or set with emery teeth. This technology was passed on to the Romans via the Greeks [13].

Tufa, or tuff, is a compressed volcanic ash. It is common in Italy and available in three forms - stony (*tufa litoide*), employed as a building stone; granular (*tufa granulare*), too soft for building stone but forms the chambers of catacombs; and sandy (*pozzolana*), used in hydraulic cement [14]. O'Conner (1993:51), quoting M.E. Blake, subdivides the building *tufas*; *capellaccio*, a widespread, very soft rock that was taken from the first layers of ash that fell near Rome; Fidenae *tufa* from the second layer; and Grotta Obscura, Monte Verde and Anio *tufa* from third. The fourth discharge of ash resulted in a layer of stone consisting of hard, dark gray *tufa* containing fragments of dark lava, white limestone and other materials. This was called *peperino*, due to its speckled appearance. A similar, but coarser, stone is Gabine

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[13] M.E. Blake has done extensive research in this area. Other authors worth consulting are D.T. Bishop, M.W. Porter and D. Hill

[14] A hydraulic cement is a cement that is capable of hardening underwater

stone. The better of these materials for building appear to have been Monte Verde, Anio *tufa* and *peperino.*

Tufa was the only stone used during the early prehistoric period of Rome, because it was both near at hand and could be worked with the available bronze tools. Simply removing the covering earth and removing the required material using hammer and chisel was all that was needed. A simple coat of stucco is sufficient to protect it from the weather, and was probably never used externally without this protection (Middleton, 1892a:5).

Lapis Albanus, modern *peperino*, is a conglomerate of ashes, gravel and other fragments of stone, all cemented together into a dense mass. It is moderately good for outdoor use, and is fireproof. It was used in parts of the Servian wall and at the exit of the *Cloaca Maxima* (Middleton, 1892a:6).

Lapis Gabinus, also called *peperino* is similar to *Lapis Albanus*, but contains less mica, is harder and more weather resistant. It contains broken fragments of lava, the product of some earlier eruption. The *Tabularium* is faced with *Lapis Gabinus*, the inner walls are of tufa. In the circuit wall around the Forum of Augustus both the Alban and Gabine stones are used, and the difference in their abilities to withstand weathering can be easily compared. The lower part of the wall is Gabine stone, and is fresh and sharp; while the upper story is of Alban stone and show considerable signs of weathering. Tacitus (*Annals*, 15.43) tells us that Nero enacted a law that required Gabine stone to be used for fronts of houses in the streets of Rome, because of its fire-resistant properties. This occured after the great fire (Middleton, 1892a:7).

Vitruvius (2.7) mentions some of these stones. He also refers to travertine (*lapis travertinus*), quarried near Tivoli or Tibur, on the banks of the River Aniene. Travertine is calcium carbonate, or hard limestone rock, deposited by hot springs, formed in a highly stratified state with frequent cavities and fissures. In it are frequently embedded bits of petrified leaves and sticks. It is strong and durable, and also has a pleasing appearance and texture, starting out with a creamy colour and weathering into a rich golden tint. In was normal building practice to face *tufas* with other materials, but travertine was used as both structure and facing. Vituvius mentions that it is a strong material, but also states that it is readily susceptible to fire damage.[15] One of the earliest known uses of travertine is on the bridge Pons Mulvius in 109 B.C. One of the most conspicuous uses is the exterior of the Colosseum (Middleton, 1892a:8).

Silex,[16] which is simply lava, was used to pave roads and broken into pieces and mixed with lime and pozzolana to form concrete. *Silex* is hard and dark gray in colour (Middleton, 1892a:8).

Pulvis Puteolanus, modern *pozzolana* existed in great quantities around Rome and Puteoli, near Naples, from which it took its name. Colour ranges from brown to brownish red and resembles a clean sandy earth mixed with larger lumps about the size of coarse gravel. The brown stone was of inferior quality and was used mostly after the 3rd century AD. This fact is a useful guide to date existing buildings. When *Pulvis Puteolanus* is mixed with lime it forms a strong hydraulic cement. Vitruvius devotes chapter six of his second book to this important material, without which the Pantheon and great vaulted Thermae would not have been possible (Middleton, 1892a:8).

High quality sand (*arena*) and gravel (*glarea*) can be found in great quantity near Rome and contributed to the strength of Roman mortar and cement. Vitruvius mentions three kinds of sand, with *arena fossitia*, or pit-sand, being of the highest quality, and *arena fluminibus*, or river-sand, next best. No sand could be better for building purposes than the golden pit-sand

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[15] When burnt, it produces high quality lime. It contributed to the durability of Roman concrete, cements and mortar.

[16] No relation to modern *silex*, which is flint.

of the Janiculan Hill. That which the Tiber deposits is not free from muddy impurities. *Arena marina*, or sea-sand, is of the lowest quality and is to be avoided for building purposes because of the salt it contains efflorescing out from the mortar or stucco (Middleton, 1892a:10). Vitruvius states that the highest quality sand can be judged by its crackling when rubbed in the hand, and by its not staining a white dress. This shows that it is both sharp and clean.

Bricks were of two types, *lateres*, or sun-dried, and *testae* or *tegulae*, or kiln-baked. Vitruvius writes only about *lateres* (2.3), and curiously never mentions the common triangular bricks that were used in all the existing Roman walls which have brick facings. His chapter on sun-dried bricks is of great interest, as it records the methods used by the Greeks as well as the Romans used to prepare this important building material. The clay was to be carefully selected and exposed to the weather for two years before being made into bricks. It was then thoroughly beaten, mixed with chopped straw and moulded into shape. They were then put in the sun to dry, but only used after a long time had been allowed to elapse. Vitruvius (2.3.2) states that, at Utica, bricks had to be kept for five years and then approved by a magistrate before they could be used. As long as they were protected by a coat of stucco these bricks were perfectly durable (Middleton, 1892a:11). In some bricks, mainly those of high quality, a quantity of red pozzolana was included with the clay, probably to prevent warping.

The existing examples of bricks in Rome are used as facing to concrete walls. No wall seems to have been made of bricks only. These facing bricks are not rectangular, but are equilateral triangles, varying in length from 10 to 35 centimetres, with 25 centimetres being the commonest size. Though the bricks for any particular wall are usually of regular size, their apparent length when seen in the face of the wall could seem to vary a great deal. This is because one or more of the sharp points of the triangle might have been accidently broken off before being set into the wall (Middleton, 1892a:11).

The bricks were laid with their ends being placed as near as possible over the centres of the triangles in the course below. The bricks (and tiles) in Roman buildings are of many colours, usually red or yellow, less commonly brown.

The *sigilla*, or stamps, which occur on the bricks of buildings of Imperial date in Rome are of great value in determining the dates of various structures. In other places in Italy brick stamps occur as early as the middle of the 1st century BC. In Rome the complete series does not begin until after the 1st century AD, and continues until circa 500 AD, in the reign of Theodoric, though not without interruptions. The inscriptions of the 2nd and 3rd centuries are usually circular, with the inscription in two concentric rings. The later stamps are usually rectangular (Middleton, 1892a:12).

Various names and facts are recorded on these stamps, such as the names of *consuls* or (more frequently) the owner of the brickfield from which the clay came, and that of the *figulus*, or potter, who made the brick. The words *ex praediis* denote the estate where the clay was dug, after it comes the name of the owner, very often the Emperor. Severus appears to have owned many *praedia*, which supplied the bricks used in his palace on the Palatine. The potter's name comes after the words *opus doliare* or *opus figlinum*, meaning "clay-work", or else *ex figlinis* or *ex officina*, meaning "from the pottery" or "manufactory". After the potter's name the phrase *Valeat qui fecit* frequently occurred, wishing the maker prosperity (Middleton, 1892a:13).

The use of brick stamps appears to have been enforced by law. This was probably in connection with a tax that was levied on bricks and tiles (Middleton, 1892a:13). The following is a example of a tile-stamp inscription in concentric rings.

> *EX . PRAE[DIIS] . DOMITIAE . LVCILLAE . EX . FIG[VLINUS] DOMIT[IANIS] . MINORIB[VS] . OP[VS] . DOL[IARE] . AELI . ALEXANDRI*

The facings of arches are nearly always made with large square tiles, about two Roman feet square. Vitruvius named these *tegulae bipedales.* They are usually cut into three or four pieces so as only to tail a few inches into the concrete arch which they hide. At intervals in each arch a few of the complete squares are introduced to improve the bond. Tiles of 30, 36 and 46 centimetres square also occur, but less commonly. There are also the small squares of about 21 centimetres which were used for the *pilae* of *hypocausts*, and also for laying over the wooden centering into which the fluid concrete to form vaults was poured (Middleton, 1892a:12).

4.9.2 Concrete

Concrete was one of two discoveries near the end of the Republican period that would immeasurably enrich the the store of construction materials available to the Romans (the other being kiln-baked bricks, or *testae.* In the vicinity of Mount Vesuvius, near Puteoli, a reddish volcanic soil was found that had useful properties. When mixed with lime, pottery fragments, sand and water in the correct proportions, a plastic mass would form that would harden, even under water, into a durable material. This material was called *pulvis Puteolanus*, and was used in construction until the invention of portland cement.

Lime was manufactured by the Romans by burning limestone in kilns and then slaking in water. The first process reduced calcium carbonate to calcium oxide, or quicklime. The addition of water converts this to calcium hydroxide, or slaked lime. Vitruvius describes this process in 2.5.1-3 and 7.2. He advised the selection of white stone, and knew of the importance of thorough slaking before use. Lime has the capacity of hardening on exposure to air; calcium hydroxide combines with carbon dioxide to form calcium carbonate, the substance from which it was originally formed (O'Conner, 1993:57).

The use of lime with sand and water to a hardening mortar was known to the Greeks, who passed on the knowledge to the Romans (O'Conner, 1993:57). The Romans in turn were able to devise or discover a means of converting this to a hydraulic cement.

It was only towards the end of the first century BC that concrete became a commonly used building material. Thus most of the aqueduct bridges used concrete. However, as many of the bridges had to be repaired and even strengthened over a period of hundreds of years, the bridges are mixtures of different materials, styles and dates (Hodge, 2002:130). Thus we find older bridges that are partially constructed with concrete; this is misleading, however, as the concrete was added later, probably to provide additional strength, as bridges were expected to carry loads exceeding that of their original design, as new aqueducts were placed above or alongside existing ones (O'Conner, 1993).

4.9.3 Pipes

Terracotta pipes called *tubuli* were the second most common material used for the construction of aqueducts, but were only suitable for low-pressure applications. They are found in some of the smaller main-line aqueducts, local urban distribution systems and even in drains. The individual sections are usually around 40-70 cm long with an internal diameter of up to fifteen cm. The length might have been dictated by the fact that they were made on a potter's wheel. They were not symmetrical, the one end was narrower than the other end so they could be joined, the narrower of one section fitting neatly into the wider end of another section, with a flange or groove to help seal the joint. A plaster, similar to the cement used in the masonry channels, was used to complete the seal. One unique method, used only in Bibracte in Burgundy, boasts a pipeline made entirely of re-used wine amphorae, their tops and bottoms knocked off so they fitted snugly into each other. The short length of terracotta pipes meant there were a large number of joints in a pipeline (Hodge, 2002:113).

A number of the pipes had openings in their tops, with removable lids, presumably to allow for cleaning. These lids would probably have leaked. One of the extant lids, now on the left wall of the vestibule of the S. Maria in Cosmedin in the *Forum Boarium*, is the **Bocca della verita**, or "Mouth of Truth". According to legend, if a liar was to put his or her hand in the mouth, it would be bitten off (Hintzen-Bohlen, 2000:364).

A metal pipe, called *fistula*, was also used. Sometimes bronze was used, but more often the less expensive lead was used (Evans, 1997:6, Landels, 2000:42 and Hodge, 2002:110).

Vitruvius prefers the use of earthen ware for several reasons (8.10). Firstly, he believed that there is a danger of lead poisoning from the formation of white lead oxide in lead pipes. Vitruvius calls this substance *cerussa.* As evidence of the ill effects of lead he points out the unhealthy symptoms shown by workers in lead smelting and casting; however, he does not know that working with lead is far more dangerous than drinking water that has passed through lead pipes. Secondly, it requires workmen with specialist skills to carry out construction, while an ordinary bricklayer can deal with earthenware pipes. Vitruvius is probably mistaken in this, as the bricklayer would have required training and experience in order to work with pipes. Thirdly, Vitruvius states that lead is more expensive than earthenware pipes. This is no doubt true. The cost of transporting lead must have been prohibitive.

The Roman method of making lead pipes can be seen in the remains at Bath in Somerset, England. A rectangular sheet of lead was folded, probably around a wooden former, into either a circle or a triangle with rounded corners. The two edges either had a simple overlap and were soldered closed, or were overlapped and folded then soldered. There were ten standard size, each named from the width of the sheet of lead used. The sized were measured in digits, one digit being 1.85 cm. Lead pipes were made in sections longer than earthenware pipes, but with thinner walls (Landels, 2000:44).

There are two problems associated with closed-pipe systems. These are pressure and sediment. If the pipe falls a long way below either the source of the delivery point, the water develops a pressure which works out at approximately $1kg/cm^2$ for every 10 metre head. If this pressure rises above the order of $3.5kg/cm^2$ it begins to have several potentially serious effects. Lead pipes tend to split open at their joins, and earthenware pipes crack along any flaws or weaknesses. The joints in sections in both tend to blow apart. This is not a serious problem when they are all in a straight line, or curved gradually up or down, since the weight of the joints is held together by the weight of the system as a whole. However, as Vitruvius points out, if there is a sharp bend between a vertical and a near-vertical section and a horizontal one, there is a great danger of bursting because the thrust of the water has to be taken by the joint itself (8.6). To remedy this problem when using earthenware pipes, Vitruvius suggests enclosing the entire elbow (or knee, as he calls it) in red sandstone (see Hodge, 2002:106).

The problem of sediment was defeated in several ways. The most effective was the settling tank. The water was fed in at one end, and if the rate of traverse was slow enough, most of the sediment would sink to the bottom before the water exited at the opposite end.

4.10 Tunnels

Approximately 80% of the total length of Rome's aqueducts ran underground. The preference for underground structures persisted long after they were called for by the threat of invasion. This was due to several advantages they had over surface structures. Firstly, they were more economical, as they required less material to build than archways. Secondly, they were not subject to wind stress or erosion that weakened the surface structures.

Thirdly, the periodic earthquakes on the Campagna damaged the underground structures less than the surface structures, and were also cheaper to repair when they were damaged. Finally, underground structures were less disruptive of surface activities (Aicher, 1995:11).

The sizes of the tunnels varied, sometimes within the same aqueduct. Typically they were about one metre wide and two metres tall, allowing room for the tunnellers and maintenance men to work. At frequent intervals the tunnels were connected to the surface with a vertical shaft named a *puteus* or *lumen.* The distance between these shafts varied between 30 and 60 metres. These shafts were equipped with handholds and footholds. They performed several functions. During the initial construction of the tunnel they allowed work to proceed at several points and not just at the two faces at opposite ends of the tunnel. They were also useful in determining the depth of the tunnel below the surface, by dropping a plumb line down the shaft. This would also serve to determine and manage the slope of the tunnel. When the aqueduct was in use, the shafts provided for air circulation and for maintenance access. Tunnels under deeper mountains, such as the Barberini tunnel under Mt. Arcese, dispensed with these shafts. Originally the the tops of the shafts were covered with lids of stone or wood (Aicher, 1995:12).

The usual method of tunnel construction, as recommended by Vitruvius, was to make the tunnel more or less straight with vertical shafts at intervals of about 35.5 metres. It is easy to ensure that a shaft is exactly vertical by hanging a plumb-bob line from a rod across the top, and ensuring that the bob hands in the centre of the shaft all the way down. A line of posts was laid over a hill, using optical sighting, and shafts sunk from them. This makes the horizontal alignment of the tunnel easier. One the tunnel reaches the first shaft it can be aligned by sighting rods under the centre of each shaft, and will more or less reliably meet up with the next along a straight line. There is some evidence to suggest that the Romans did not trouble to get the gradient exactly right at the initial stage, but corrected it later by making a channel in the floor of the tunnel, which could be adjusted a little up or down as required (Landels, 2000:39).

When digging a tunnel from both sides of a hill or mountain, there is always the possibility of the two ends not meeting. The error can be planimetric or altmetric. The altimetric is the more serious of the two possible errors, and could mean that one half of the tunnel was simply not usable. The best case altimetric error results in a small waterfall in the tunnel. If the water were to flow the other way, the result may be the formation of a dam. Planimetric errors are more acceptable. These can usually be corrected by connecting the two halves of the tunnels by digging at an angle from one end until the two are joined (Taylor, 2007:75).

The longest tunnel used by the Romans was probably used in the Anio Novus. It was about 2.25 kilometres long. No trace of it survives, but its existence is attested by the presence of otherwise impenetrable hills that cross the line of the aqueduct. Shorter tunnels between 50 and 400 metres were not uncommon. If possible, tunnels were made by sinking a number of vertical shafts and tunnelling in both directions from the bottom of each. Once the channel or tunnel is made, the shafts provided ventilation and easy access for inspection and maintenance. An experienced miner could spot the points at which subsidence or collapse might be expected and promptly stop the leak (Landels, 2000:39). The shafts might also serve to release air pressure that might form when the inflow of water increased sharply. The openings were usually round, sometimes square. It is not known whether the Romans were influenced by the one great advantage of a round manhole cover over a square one, it is impossible to drop the lid through the hole (Hodge, 2002). Occasionally the ridge or hill that needed tunnelling was too high, making vertical shafts impractical. The tunnel was there driven in one continuous bore, either starting at one side and continuing until the tunnel was complete, or starting at both ends and meeting in the middle. The latter was probably the normal method, as it cut the working time by as much as half. This method faces the problem of orientation, and indeed there are examples of "misses", such as in Saldae in North Africa. An inscription by Nonius Datus, an army engineer, complains how the two halves of the tunnel missed each other by so much and the workers continued digging for so long that they almost had two tunnels (Hodge, 2002:128 and Landels, 2000:53).

4.11 Measuring capacity

Measuring the discharge of the aqueducts is no easy task. The most accepted modern figures per aqueduct are found in Table C. Frontinus gives us figures for the aqueducts extant at the time of his office, but his figures are probably not all that accurate. The discharge cannot be measured as a cross section of the channels, as they were never filled to capacity, nor is it easy to judge the actual amount of water in the channel. Frontinus does specify that measuring equipment for recording discharge is often installed in a piscina. He does not actually specify what the equipment is, and it seems that there would have been difficulties in using it in the piscina, such as darkness and the awkwardness of working in a covered tank full of water. The approximate daily output has been determined to be between 520,000 m^3 (520,000,000 litres) and 1, 125, 880 m^3 (1, 125, 880, 473 litres) per day.

The rate of flow of each aqueduct was calculated in *quinariae*. It is perhaps an impossible task to determine exactly what a *quinaria* was, but scholars have calculated that one *quinaria* was equals to 0.48 litres/second. The most powerful of the eleven aqueducts, the Anio Novus, drew 4,738 *quinariae*, which meant a supply of almost[17] 200 million litres per day (see Hodge, 2002:347, Landels, 2000:52 and Middleton, 1892b:349).

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[17] There are 86,400 seconds in a day. A rate of 4,738 *quinariae* equals 2274.24 litres per second. The product of 2274.24 and 86,400 is 196,494,336.

4.12 Maths

Trigonometry, the basis for modern surveying, was unknown in Rome. Geometry, which had been developed into a sophisticated art, was applied to the task of surveying instead. Surveyors knew how to calculate the areas of triangles, rectangles, some polygons and even to a certain extent, circles. The Romans were aware of the insights of Thales, Pythagoras and Euclid.

Diophantus, who lived somewhere between the first and perhaps as late as the third century AD in Roman Egypt, is taken by many historians as being the father of algebra (Derbyshire, 2006:31).[18] Algebra is a valuable mathematical tool in the design and planning of all aspects of project management and civil enginering. However, Diophantus took the stage a little late for his work to be of use in the construction of the Roman aqueducts.

In some cases, cleverness can compensate for a lack of knowledge. For example, it is easy to find the distance to a point on the opposite side of a river using triangulation, a technique of trigonometry. The Romans used a geometric method instead, one based on equal triangles. A groma, a tape and a few poles were all the equipment that was needed (Hauck, 1988:45).

What probably gave surveyors and engineers the hardest time was not geometry, but arithmetic. The Romans used a number system that was decimal based, but units that were not. They also lacked decimal fractions and had to use true fractions in calculations (Hodge, 2002:296). This made it difficult to evaluate the square root of integers, and to evaluate the number π.

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[18] Others prefer al-Khwarizmi. Both made valuable contributions to the advancement of mathematics.

Chapter 5

ELEMENTS OF AN AQUEDUCT

5.1 Introduction

The aqueducts of Rome are a system of many parts, each contributing to the overall functionality. Each part required different materials and sets of skills to build. Each part had its own set of problems and different maintenance requirements. This chapter will briefly examine these parts, though the case can be made that each of them deserves its own chapter.

5.2 Water storage prior to the construction of the aqueducts

Some of the early rock-cut cisterns for storing spring water and the well shafts which connect to them, still exist on the Palatine (Middleton, 1892:315). Other springs of water, such as the *Fons Jaturnae* in the Forum were preserved for ornamental and religious reasons. A large proportion of the streams which once formed open brooks, draining the main valleys of Rome, were after the growth of the city and the construction of the aqueducts, no longer allowed to run along the surface if the ground but were redirected into the *cloacae* (Middleton, 1892:315).

5.3 Cippi

One interesting feature that seems unique to the aqueducts of Rome is the *cippi*[1]. A *cippus* was a small stone marker set in the ground. It performed two functions; where the channel ran underground the *cippi* marked its location and since they were numbered like milestones, they gave the maintenance staff a convenient point of reference to any point on the line. No *cippi* have been found anywhere but on the aqueducts of Rome, and then not on all of them. Frontinus tells us that instituted by Augustus, who installed them on existing aqueducts and on new construction and renovation.

Hodge (2002:103) states that *cippi* were usually placed 240 Roman feet apart, about 71.3m. However, in practice, the placement varied. Not enough have been found *in situ* to make a definitive judgement on the matter. Hodge also notes that they may not have been used much, and were probably unique to Rome. See Chapter 3.5 for an example of a *cippus*.

5.4 Channels

Channels could be open or closed. Most ran within one metre of the surface of the ground, and were probably built using the cut and cover method (Hodge, 2002:93). In this method, a hole was dug, the channel was constructed and then covered with earth. However, occasionally aqueduct channels were open to the air, especially when they traversed rock. This was more common in provincial aqueducts than in those that supplied Rome. A channel was typically lined with concrete and the roof vaulted.

Another benefit of using channels was that they could be smaller than the conduits that ran on arches. Those conduits were large enough to allow

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[1] Literally, "a gravestone"

men in them for maintenance purposes. An open channel could be a little smaller, as there would be enough space for a man to manoeuver if the roof was removed - a relatively easy process in the case of stone slabs and vaulted ceilings.

5.5 Pipes

According to Vitruvius, water could be conducted in three ways (8.6.1):

> *Water can be conducted in three ways: by flow in masonry channels, lead pipes and terracotta pipes.*

Pipes were not only made of terracotta, lead and stone, but also of wood. The use of all four has been found in Roman aqueducts (Hodge, 2002:106). Terracotta was the most common, followed by lead and then stone. Wood was rare in southern Europe, but more common than stone and lead in northern Europe and Britain. Pipes are more difficult to maintain than open channels, so it is likely that, and the evidence suggests, that pipes were used less than channels. Nonetheless, both Vitruvius (8.6.1) and Pliny (*Nat.His.* 31.57) provide detailed specifications for the use of pipes.

Figure D.20 shows three clay pipes tapped into the Aqua Claudia.

5.6 Bridges

According to O'Conner (1993:151), the total length of the aqueducts at Rome was 507 kilometres. 434 underground, 15 on the surface and 59 on bridges. This makes only 11.6% on bridges, unless you take into account that some briges counted for more than one channel, so the total is closer to 5%. See Figure D.14 for a crossection of a typical aqueduct above ground.

According to O'Conner (1993:203) only six of the eleven Roman aqueducts have significant remains of bridges. These are the Marcia, Tepula, Julia, Claudia, Anio Novus and Alexandrina. The most impressive remains of aqueduct bridges span the valleys and ravines between Tivoli and the Alban Hills, in the area between the modern town of Gallicano nel Lazio and the village of S. Vittorio (Aicher, 1995:113).

One of the most important, and impressive, remaining bridges is the Ponte Lupo, just south of the road to Poli. It is a massive and confused mass of original stone and concrete repair, 115 metres long and 30 metres tall. The evidence show that this bridge carried the Aqua Marcia. Van Deman (1934) provides a succinct summary of the bridges history.

> *This colossal structure, an epitome in stone and concrete of the history of Roman construction for almost nine centuries, is composed of two lofty arches of early cut-stone over the stream with heavy abutments of Augustan concrete on both banks, enclosed, but a few years later, in walls of concrete of the same general type, which, in their turn, were reinforced by massive walls at least three times in as many centuries, with extensive later repairs.*

The Ponte Lupo was originally built in 144 BC out of cut-stone quarried from the tufa slopes on the valley's left bank near the bridge. The only remains of the structure are the two tall arches that are clearly visible at the stream. A century later the bridge had deteriorated badly enough to necessitate almost complete replacement. Agrippa, rather than shoring up the original structure, replaced all but the two central stone archways. Agrippa's engineers were the first in Rome to use concrete in the construction of aqueduct arches and they built a bridge that was too airy for this material. Nero's engineers were to repeat the mistake in the next century. Within a few decades Agrippa's work was again shored up by adding encasing walls. Titus found it necessary to repeat this in 79 AD. Hadrian found it necessary to add a few encasing walls and buttresses, but nothing as dramatic as the former repairs. Caracalla's repairs of 212 AD were more substantial, and the bridge required only minor repairs less than a century later. The resulting work is a conglomeration of construction techniques and materials that, while not following Vitruvius' admonition that structures should be beautiful, was certainly strong and useful.

There was a limit to the height to which the Romans built the arches over which aqueducts were carried. It is possible for a tall pillar to fold sideways in the middle during a high wind or if subsidence had taken place a the base. If one pillar gave way, it could cause a progressive collapse of the whole series of arches. The Roman solution was to limit the height of the arches to about 21 metres. When they worked near this limit they made the pillars very massive, and the arches between them narrow. If a greater elevation was required, the Romans built the arches in two tiers, the pillars of the upper resting directly on those of the lower. The arches of the lower tier could me made simple and not very heavy, their sole purpose being to brace the pillars from each side. They consisted of the solid wedge-shaped stones which formed the arches themselves and shaped stone forming a level top course above the arch. The structure above the upper tier was exactly like that on a single-tier aqueduct (Landels, 2000:47).

When the aqueduct had to cross a deep valley, and for some reason the engineers had decided not to use a siphon, the same principle was used, but carried a stage further by the addition of a third tier of arches. The most famous example of this is the Pont du Gard. This technique does not appear to have been used near Rome, probably because it was not necessary to do so.

According to Taylor (2002), only one of the bridges that crossed the Tiber carried an aqueduct exclusively, the Pons Traiani. Until 109 AD, when the Aqua Traiana was built, most of the water in the Transtiberim (the west side of the Tiber) had to be supplied from the east bank by means of inverted siphons carrying pressurised water in pipes across existing bridges. The most notable of these was Agrippa's Aqua Virgo and Nero's Claudia-Anio Novus system from the western Caelian hill. When Frontinus was writing in the late first century AD three other systems also fed the Transtiberim, namely the Aqua Appia, the Anio Vetus and the Aqua Marcia. These crossings may initially have been the work of Agrippa, who as aedile in 33 BC had restored and expanded the water system throughout Rome. In the following decades a number of new water sources became available, including new branches of the Aqua Appia and the Aqua Marcia, new aqueducts in the form of the Aqua Julia, Aqua Virgo and the specialised Aqua Alsietina. When possible, the river crossings were probably added to existing bridges. The distribution point of the Aqua Appia was at the Porta Trigemina in the Salinae, making the likely crossing to have been on the Pons Aemilius. The crossing sites of the Anio Vetus and the Aqua Marcia are less certain, but there are few options. The Pons Cestius might have been built by order of Agrippa to help carry his planned load of aqueduct siphon pipes. The funerary inscription of C. Cestius indicates that he was a partisan of Augustus. Doubtless Agrippa built the Pons Agrippae with a similar purpose in mind. There is evidence that the Aqua Virgo crossed the Tiber on this bridge (Taylor, 2002:16). It can only be a matter of conjecture which bridges the other aqueducts used, but it is likely that the largest (for example, the Claudia-Anio Novus) had multiple crossings on whatever bridges were available.

The reference to the Pons Traiani appears only once, in a late source (Taylor, 2002:17). It is usually taken as a mistaken reference to the Pons Aelius, the bridge Trajan's successor Hadrian built. Taylor has argues that the Pons Traiani is a separate bridge and can be identified on maps of the early modern period. Taylor's view is that it was exclusively an aqueduct crossing and offered no transit for traffic. It is for this reason that it is not included in the various extant lists of traffic bridges. As the Pons Traiani would have served as the support for a free-flow channel of water it would have been more prominent than its neighbours, rising (in Taylor's view) perhaps as high as 35 metres above the surface of the water. The ruins of bridge piers that plausibly may have been the Pons Traiani appear in a map by G.-B. Nolli in 1748, and are reproduced in a map by Lanciani.

According to Taylor (2002:17) the Pons Traiani bore the Aqua Traiani across the Tiber. This was the sixth and last aqueduct to cross the Tiber, and the only one to cross from west to east, as unlike most of the aqueducts, it arrived in the city from the west. There is epigraphic evidence that the Aqua Traiani served the entire city. As most of Rome's population was on the east bank, it is sensible that Trajan's engineers would build a free-flow channel across a river instead of using a siphon pipe; the volume of water would make using siphons problematic.

It is worth mentioning that what is called a bridge is sometimes actually a viaduct. Technically, a bridge carries a route across an obstacle such as a river or gorge where intermediate support is difficult or impossible. A viaduct carries a route across a dip in the land where almost continuous support can be provided, and the purpose of the structure is to maintain the level of the route. With a bridge, the emphasis is on a wide, clear span, while with a viaduct it is on height (Hodge, 2002:130). Thus, as many Roman aqueduct's had to cross a valley while maintaining a level route, they are technically viaducts.

5.7 Substructio

If a hill intervened on the course of an aqueduct and there were sufficient masons available and a ready supply of local stone, a channel was built around the hillside. This would follow the contour line except for the slight fall required to maintain the flow of water. The channel was supported on what was in effect a low, broad wall. This was faced with stone on the outside and filled with rubble. Thin slabs of stone formed the bed and channel, covered with a lining of cement to make it waterproof. This was named *substructio* by the Romans. There were a number of serious drawbacks to this kind of construction. It was labour-intensive to build and expensive. It was exposed to pollution. And it was vulnerable to damage in the event of a siege. The alternative of building a tunnel was thus generally preferred (Landels, 2000:38).

5.8 Siphons

One way by which natural features such as valleys and depressions could be crossed was the *inverted siphon*, a technique based on the simple physical principle that "water finds its own level". The Romans were well aware of this principle, as Pliny puts it - *subit altitudinem exortus sui* (*Hist. Nat.*, 21.57). They took advantage of this fact by constructing pipes reaching to the tops of high fountains and to supply the upper rooms of houses (Middleton, 1892:316). On occasion the Romans would cross the lowest portion of a valley on a bridge, whether to reduce water pressure that increased with the vertical drop of the pipe, or to form a level and sturdy bed (Aicher, 1995:17).

Just before a downward slope, water was collected into a cistern, from which a pipe carried it to the bottom of the hollow by gravity, and then up again into a second cistern, thanks to the pressure generated along the first slope. A small viaduct was sometimes built on the bottom of the hollow to reduce its maximum height, thus to minimize the water pressure needed to climb the opposite side. Figure D.19 shows an illustration of such a siphon. Figure D.34 shows a cistern on the Aqua Marcia, near the villa Vignacce with the Marcia, Tepula and Julia in the background, near the Via Lemonia.[2]

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[2] This section conducts water from the Acqua Felice. This was completed by Pope Sixtus V in 1586, and was the first new aqueduct of early Modern Rome. It is 24 km long, running underground for almost 13 km from its source, first in the channel of Aqua Alexandrina, then alternating on the arches of the Aqua Claudia and Aqua Marcia for 11 km to its terminus at the Fountain of Moses on the Quirinal Hill.

Many modern sources state that the siphon was not often used for Roman aqueducts, and give a number of reasons for this. For example, pipes available in Roman times, made of lead or earthenware, could not be soldered steadily enough to hold the rather strong pressure generated by the slope, causing a substantial loss of water and requiring frequent repairs. Another example often mentioned is that they did not know of its existence. Some modern sources even state that the Romans had failed to realise that "water finds its own level". However, it is clear from the writing of Archimedes, Hero and Vitruvius that the Greeks and Romans had a thorough grasp of the pressure-equilibrium principle (Landels, 2000:43), if not from their engineering accomplishments.

As Hodge (2002:147) points out, the Romans did in fact use inverted siphons. They were both numerous and successful. Hodge gives two possible reasons why modern scholars often write as if the Romans did not use them. Firstly, there might be ignorance of evidence, arising from the circumstance that siphons are very rare on the Rome metropolitan network, and this is where study has been concentrated. The second is a misapprehension of the hydraulics involved, in particular what Vitruvius has to say about them. Vitruvius said that siphons create pressure and steps have to be taken to deal with it. This is then garbled into statements that Romans tried to avoid pressure systems, and sometimes that they did avoid them and that such systems did not exist. Middleton (1892:316) states that the reason the Roman engineers did not use the siphon often was economical: lead and bronze were very expensive and had to be brought from some distance away. The amount of lead needed to manufacture an inverted siphon is considerable. Hauck (1988) states that one of the reasons for building the Pont du Gard may have been because of the prohibitive cost of purchasing and transporting enough lead to build enough inverted siphons to carry that amount of water. Middleton also points out that it is convenient to employ channels which were readily accessible for maintenance purposes.[3] Landels (2000:43) states that siphons are more difficult to construct and require specialised skills. He also states that the lead pipes were more prone to bursts and leakage, and the conduit itself was not accessible in case of blockage. Sections or entire pipes would have to be replaced.

The architects, instead, in most cases preferred to lengthen the course of the aqueduct, sometimes quite considerably (as in the case of the Aqua Virgo), so to follow the ground's natural features and constantly meet a regular slope. This, according to Frontinus, is the reason why most aqueducts were much longer than the direct distance between their source and their urban output. Middleton (1892:317) finds this description unsatisfactory. He states that step-like falls of water could have been arranged at required points along the course of the aqueduct, and would have shortened the length considerably.

There is additional evidence against the commonly believed that the Romans did not make use of siphons. The Beaunant siphon of the Gier aqueduct serving Lyon had a drop of 123 metres and was 2.6 kilometres long (Aicher, 1995:17). What is true is that there is little evidence for their use in Rome itself, though Ashby (1935) does point out that the Capitoline and Palatine Hills were supplied by siphon. Evans and Bruun are in agreement with this. Evans (2000:90) states that the Marcia's higher level made delivery of water to the Palatine possible, and that it is probable a siphon was used.

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[3] The Croton Aqueduct in New York, constructed between 1837 and 1842, was similar to the Roman aqueducts in many ways. It also did not employ siphons for the reason of cost.

5.9 Dropshafts

Chanson (1999) believes that the use of dropshafts to trap sediment would not have worked unless with very heavy particles that would damage the conduit mortar. Chanson states that Roman dropshafts might have been used for one of three purposes: a vertical drop in invert elevation, kinetic energy dissipation and flow aeration. In the first application, a dropshaft allows the connection between two conduits located at different elevations within a short distance. The second application is common and is still used today. Ervine & Ahmed (1982) have investigated the use of dropshafts for aeration thoroughly; the interested reader is directed to them.

5.10 Castellum

Water from the aqueducts was usually channelled to a tank or terminus known as a *castellum*[4] to store and filter it. All that was needed to filter the water was essentially a large tank where the speed of the current would be sufficiently retarded for the impurities in suspension to settle to the bottom. More elaborate filtration methods where also used. For example, a *castellum* might have two chambers set at different levels. The water would arrive in the lower chamber and leave from the upper chamber. At Cirta in Algeria a filter made of sandbags was used, though nothing like this has been found in Rome. A Castellum[5] was also built where the water was channelled to public collecting tanks. As the number of aqueducts increased, favoured individuals were granted ”private” supplies; water was diverted to their private residences. Once collected in the distribution tank, the water was carried out to various places through lead or tile pipes (*fistulae*), which were connected to the *castellum* by a tap called a calix. Fistulae transported water to many facets of the city; private, public and imperial. An interesting

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[4] Although most castella belonged to the state, when enough private users existed to justify it, and they could afford it, they could build a private *castellum* at a location approved by a waterworks inspector (Hodge, 2002:294).

[5] There are 247 known Castella in Rome (Hodge, 2002:291). See Table C.5.

phenomenon, regarding the distribution tank, is the law governing the hierarchy of delivery. Vitruvius' treatise on architecture explains this hierarchy (8.6.1-2):

> *When it [the water] has reaches the walls of the city, build a reservoir (castellum aquae) and adjoining the reservoir a three-part reservoir compartments connected with the reservoir to receive the water. Within the reservoir lay three systems of pipes, one for each of the connecting tanks, so that when the water runs over from the tanks at the ends, it may run into the central tank. The piping system for all the public pools and running fountains should be put in the middle tank; pipes for the baths in one of the outside tanks, to provide tax revenue every year for the people of Rome; and in the third tank the piping system should be directed to private homes, so that there will never be a shortage of public water for private citizens will not be inclined to divert public supplies if they have their own supply from the same source.*

The philosophy of water distribution thus seems to favour public good over private gain. A *castellum* as described by Vitruvius would have three pipes for distributing water, one slightly lower than the other two, supplying public fountains. If the water level dropped, then the lower pipe would still receive a full supply, but the upper two pipes would receive progressively less water. The aqueduct's primary purpose, in theory, was to provide the masses with a good supply of water. There was a water tax, and this was determined by the size of the calix that was connected to the distribution tank. A premium was charged for all private deliveries.

Frontinus supplies a great deal of information on the methods by which supplies were measured and assessed for tax. Here we meet the contrast between the understanding of the static, and the lack of understanding of the dynamic. No attempt seems to have been made to measure the speed at which water flowed through a pipe or conduit. The entire technique seems to have been based on the size of the calix. Why this is is not known. The Romans certainly had some knowledge of water pressure. For example, t was known that if the gradient of the channel was steeper, the speed of the flowing water would increase. Vitruvius also discusses pressure in reference to inverted siphons. Frontinus makes no attempt to explain this. Under normal circumstances a calix of a specific size delivers a certain amount of water to a customer, but in the case of a steeper channel or extra rain in the catchment area more water than normal would be delivered (Landels, 2000:49). This seems to be simply regarded as a bonus for the recipient of the water. Frontinus does write of making some adjustment if the rate of flow differs from the normal (1.35):

> *Let us remember that every stream of water, whenever it comes from a higher point and flows into a reservoir after a short run, not only comes up to its measure, but actually yields a surplus; but when ever it comes from a lower point, that is, under less pressure, and is conducted a longer distance, it shrinks in volume, owing to the resistance of its conduit; and that, therefore, on this principle it needs either a check or a help in its discharge.*

Frontinus also recognises that the position of the *calix* is important, not just the size. He states (1.36):

> *But the position of the calix is also a factor. Places at right angles and level, it maintains the normal quantity. Set against the current of the water, and sloping downward, it will take in more. If it slopes to one side, so that the water flows by, and if it is inclined with the current, that is, less favourably placed for taking in water, it will receive the water slowly and in scant quantity.*

Frontinus takes a number of pages to describe all the *calixes* in detail (see C.6 for a list of the most common sizes). He (1.37) states that of the

25 available, only 15 are in use.

5.11 Piscinae

In order to remove impurities and particulate matter from the water, settling tanks (piscinae)[6] were installed at various points between the source and castellum. Subsidiary lines (ramus) were also employed along the course, in order to augment the capacity of the line or cool the temperature of the water. The ramus did not always terminate in the same castellum as the main line. Sometimes small settling pits set in the floor of the ordinary channel supplemented the piscinae (Hodge). Another problem was incrustation, which occurred at varying rates according to the hardness of the water. Polishing the cement in the channel served to alleviate this problem somewhat, but deposits of calcium carbonate and lime carbonate (also known as *sinter*) could choke the channel by as much as 50%. Pipes were an even bigger problem, as a pipe is likely to be full any layer of deposit reduces the cross-section by the square of the reduced diameter. Thus sinter had to be removed more often from pipes than cfrom channels. If the pipe consited of lead, this was easy. According to Fahlbusch, lead pipes could be cut open, the sinter broken out, and the pipes soldered closed again (Hodge, 1991:8). Fahlbusch also speculates that boiling vinegar might have been used to remove sinter(Hodge, 1991:9).

Interestingly, the incrustation of sinter could become so thick that it was sometimes cut and used in construction. In appearance it is very much like travertine and was often used in churches as a decorative veneer. Noteworthy examples of this are the altar in the church of Kreuzweingarten near Cologne and a headstone in the cemetery of the same. The headstone dates to 1964 A.D. (Hodge, 2002:233).

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[6] Only three of Rome's aqueducts lacked piscinae, the Appia, the Virgo and the Alsietina (Hodge, 2002:274).

The incrustation of sinter provides another benefit for the historian and archaeologist; sinter can be used for comparative dating, much like tree-rings can be used (Hodge, 2002:99). The information that can be extracted is, of course, limited to the last removal of the sinter. This at least places boundaries on dating, and while not providing an accurate date, certainly improves any estimates.

5.12 Naumachiae

Though not strictly part of the aqueduct, the *naumachiae* is still part of the overall water-system of Rome. It was constructed by Domitian for naval spectacles. According to Cassius Dio (67.8) it was a new place, so most topographers conjecture that that it was on the right bank of the river. However, all of his other buildings for shows were in the *Campius Martius*. According to Suetonius (*Dom.* 5), Trajan used stone from the *Naumachiae* to repair the Circus Maximus after a fire. There is some evidence that Trajan built his own *Naumachiae*. This would probably have had a non-trivial impact on the management of the water supply. Either they needed a supply of water to constantly refresh them in order to avoid turning them into mosquito breeding grounds, or they were only filled when needed and then emptied. Either way, a considerable anount of water would have been required for them.

5.13 Taps

Landels (2000:52) asks the question: if a Roman householder had a piped supply of water, did he (or she) have a tap to turn it off? Neither Vitruvius not Frontinus makes any mention of a tap. This fact may mean nothing more than that they saw no reason to mention such a common device. If there were no taps, then presumably the water ran from a spout into a basin, from which it flowed away. It may have been used to flush a lavatory, in much the same way as at public buildings.

5.14 Conclusion

The aqueducts of Rome consisted of a system of many interrelated and interacting parts. Following the Roman tradition of ensuring that construction of impressive and durable buildings, most of the aqueduct system require no more than standard artisans skills. However, it is likely that aqueduct construction advanced the use of cement and, to some extent, metallurgy. The construction, planning and maintenance of the aqueduct system also have contributed to the Romans ability to think on a systemic level, without which the administration of such a large city as Rome would not have been possible. Some of the elements of the aqueduct systems, such as the *Naumachiae*, would have increased the demand for water.

Chapter 6

ROMAN AQUEDUCTS

6.1 Introduction

It is generally agreed that the city of ancient Rome had eleven major aqueducts[1] built between 312 BC and AD 226 and possibly a few minor aqueducts, probably between eight and twelve in number. The evidence for the majority of the minor aqueducts is not substantial, and they must perhaps remain little mysteries. The first major aqueduct was built in 312 BC and the last around 200 AD. Some of the aqueducts outlasted the Empire and remained in use well into the middle ages; parts are still in use. The quantity of water carried by the aqueducts is one of Rome's most impressive achievements.

Though we have a number of estimates of the total volume of water the aqueducts delivered [2], Frontinus faced a number of problems when trying to make this measure. He found that the aqueducts delivered more than the records indicated (2.64):

> *Now there were, in the aggregate, 12,755 quinariae set down in the records, but 14,018 quinariae actually delivered; that is, 1,263*

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[1] See Table C for a list of the 11 traditional aqueducts.

[2] Hodge's figure of 1,127,220 cubic metres of water per day is perhaps the most accurate

> *more quinariae were reported as delivered than were reckoned as received.*

Such a large discrepancy demanded an investigation. The investigation initially deepened the mystery:

> *Accordingly, I first undertook measurements of the intakes of the conduits and discovered a total supply far greater - that is, by about 10,000 quinariae - than I found in the records.*

There are another two complications. Firstly, about one third of the water was actually distributed outside Rome (Evans, 1997:140). There are also problems with Frontinus' techniques of measurement. However, more importantly, water theft was rampant. Often small-gauge offtakes would be inserted into main pipes and conduits to steal water. Often these were not well-installed, and severe damage to the main pipe or conduit resulted. For example, placing the offtake in loosely might result in a leak, or the expulsion of the offtake pipe due to pressure. Too many offtakes in close proximity might result in the main pipe or conduit collapsing. Frontinus states that they may be "*ripped apart*".

These two complications make an already complex task more difficult. We must satisfy ourselves with the estimates we have, and try to improve them if new information or insight arises.

6.2 Rome and its environs

Rome is situated on the Tiber River, which follows a structural depression created late in the geologic history of the region, when the land was being pulled apart by movements of the Earth's crust. The river's basin is one of the largest on the narrow Italian peninsula. Most of it's 403-kilometre length runs parallel to the Apennines across Tuscany, Umbria and Lazio before it enters the sea at Ostia. The Tiber drains a huge area, more than

17,000 square kilometres (Heiken, Funiciello & De Rita, 2005:65). The river rises in the Apennines, near Arretium (Speake, 1995:635). This is in modern Emilia-Romagnaan administrative region comprising the two historic regions of Emilia and Romagna.

The key structural feature of the peninsular of Italy is the presence of the Appennines. They run from continental Italy through a length of 1000 km, cover a breadth of between 50 and 100 km, down to Sicily. Less than 20% of the peninsula is lowland (Stoddart, in Rosenstein & Morstein-Marx, 2006:103). The Apennines are structurally complex, made mostly of sedimentary rocks that were deposited in ancient seas, subjected to high temperatures and pressures while deeply buried, consolidated and then thrust up to their present elevation. These rocks are mostly limestone [3] and dolomite [4]. Over time, slightly acidic rainfall cuts into these rocks and dissolves them, creating networks of caves and fissures, known as *karst* terrain[5]. The central Italian Apennines contains karst terrains over an area of about 8,000 square kilometres, and it is calculated that this supports a cumulative groundwater outflow of 220,000 litres of water per second (Heiken, Funiciello & De Rita, 2005:37).

The Tiber enters Rome from the north, then turns southwest towards the Tyrrhenian sea. The hills west of the Tiber are composed of million-year-old marine mudstones and sandstones, giving evidence that once the region was beneath the sea (Heiken, Funiciello & De Rita, 2005:11).

Eruptions in volcanic fields located southeast and northwest of Rome created two plateaus that descend towards the Tiber. Flows of ash and gas from

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[3] Mostly calcium carbonate ($CaCO_3$), with traces of other elements (Blyth & de Freitas, 1986:124)

[4] A magnesium-calcium carbonate ($CaMg(CO_3)_2$), a non-silicate mineral (Blyth & de Freitas, 1986:83)

[5] Named after the Karst area of Istria in the former Yugoslavia Serbia and Montenegro) which has this characteristic terrain (Blyth & de Freitas, 1986:32)