Roman Aqueducts & Water Supply

A. Trevor Hodge

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The Aqueduct

It must be admitted, this is the greatest wonder the world has ever seen.

Pliny, *NH* XXXVI, 24, 123

The aqueduct channel

We have now tapped the water supply at source or spring, and turn to the means whereby it was transported to the city – the aqueduct. To most people, familiar with pictures of the great bridges and arcades, arches and aqueducts are largely synonymous. One forgets the rest of the aqueducts, for which Vitruvius[1] specifies three types of conduit: masonry channels, lead pipes and terracotta pipes. In fact, the arches, despite their prominence and fame, are always a rarity considered against the total length of the Roman aqueducts. And in spite of Vitruvius' offer of a triple choice of materials for the conduit (as we shall see, there were actually not three but six materials in common use), there was only one generally employed in the circumstances we have envisaged. We can thus produce, as it were, a portrait of a typical section of Roman aqueduct, and this reconstruction will be true of some 80 to 90 per cent of the total mileage of all Roman aqueducts everywhere in the empire.

The typical Roman aqueduct was a surface channel. By this I mean a conduit that closely followed the surface of the land, instead of being raised on arches or sunk deep beneath it in a tunnel. To protect the channel it was usually some 50 cm to 1 m below ground (as in Fig. 46), and on this basis is often, not unreasonably, described as a subterranean aqueduct. Today it is intermittently traceable in spots where the channel has collapsed or been interrupted by modern excavations, such as roadworks; or where it perforce emerged from underground in order to maintain its level in uneven terrain. Sometimes it was equipped with vertical inspection manholes at regular intervals which reveal the presence and course of the channel below. But such a structure does make the conduit hard to detect from a surface survey, and whole aqueducts of this type have remained untraced, though known to exist.[2]

Presumably, being only a metre or so underground, the channel was normally built on the 'cut and cover' principle – that is, by digging an

46. Cologne, Germany: a stretch of the Eifel aqueduct, showing vaulted roof and an inspection manhole; normally subterranean, this section was uncovered during road-building (photo: K. Grewe, Bonn).

open excavation, constructing the conduit, and then covering it over again, as opposed to tunnelling proper.[3] The channel was built of masonry, and since the great majority of aqueducts, especially in the provinces, were built during the empire and hence post-date the widespread adoption of concrete in Roman structures, concrete and rough stone construction is common. So is brick. Cut and fitted stonework, such as we see in the Pont du Gard or the arcades of the Aqua Marcia, is very rare in a surface, or subterranean, channel.[4]

In cross-section the conduit normally formed a tallish oblong: its size naturally varied, but the figures for the Marcia (90 cm wide by 2.40 m high) and the Brevenne (Lyon: 79 cm by 1.69 m) give the general proportions.[5] The roof was usually formed by a vault (Fig. 46), sometimes recessed back from the tops of the vertical side walls to form a ledge on which the wooden centering could rest during construction, sometimes flush with them. Less commonly the channel was roofed with a flat stone slab, or occasionally a pair of flat slabs tilted in to meet and form a pointed roof[6] (see Figs 48, 49).

The reason for these proportions must be clearly understood. The channel had to be accessible to a man for maintenance and cleaning, and

46. Cologne, Germany: a stretch of the Eifel aqueduct, showing vaulted roof and an inspection manhole; normally subterranean, this section was uncovered during road-building (photo: K. Grewe, Bonn).

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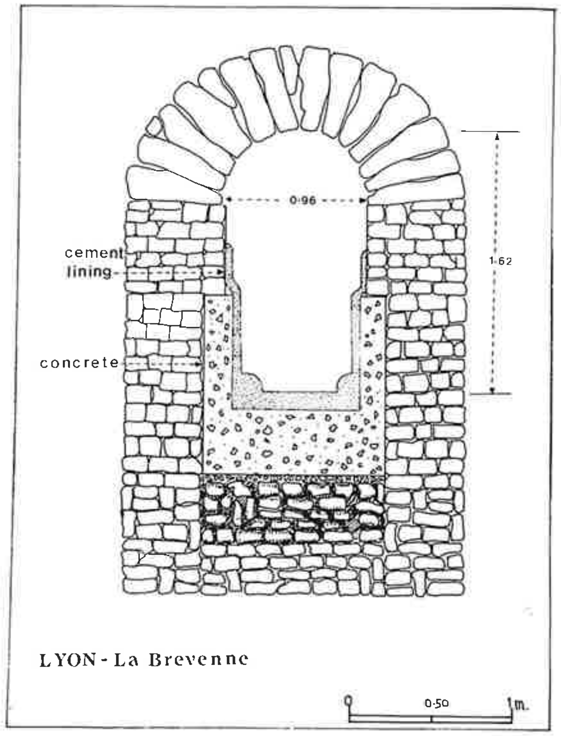
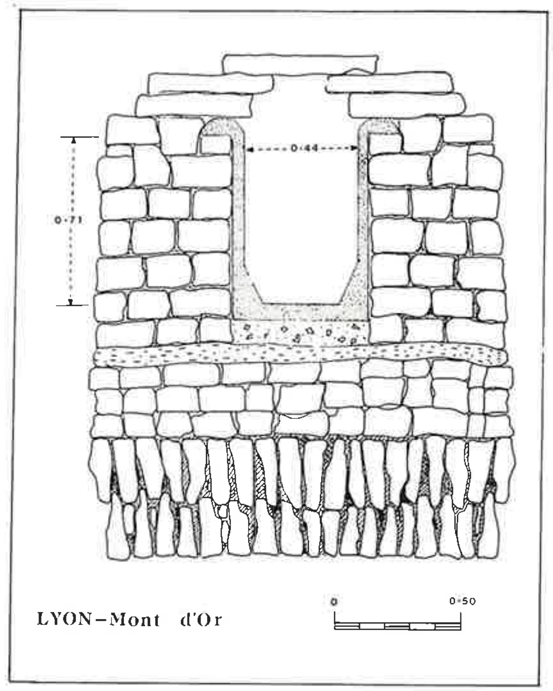
47. Pont du Gard: the conduit of the Nîmes aqueduct, a short distance to the south of the great bridge. The channel, here running at ground level, has lost its vaulted covering but clearly shows the thick *sinter* incrustation on its sidewalls.

it was this factor that governed its size, not the volume of water to be carried.[7] In fact, the channel was normally only half to two-thirds full of water (which has the incidental result that calculations of the aqueduct's discharge cannot be based on a simple cross-section of the conduit), and was never intended to carry more. Overflows in the side walls were occasionally provided to ensure that it did not, though sometimes this might happen by accident as the water blocked back before some bottleneck or obstruction.[8]

The floor and side walls were lined with waterproof cement, though sometimes not all the way up to the top but just as far as it was thought the water would actually rise. Sometimes in the two bottom corners of the



48. Lyon: (above) cross-section of typical aqueduct, showing vaulted roof, foundations and cement lining of channel (aqueduct of La Brevenne); (below) channel with corbelled roof. The top cover slab could be lifted to facilitate cleaning (aqueduct of Mont d'Or) (Cl. Lutrin).



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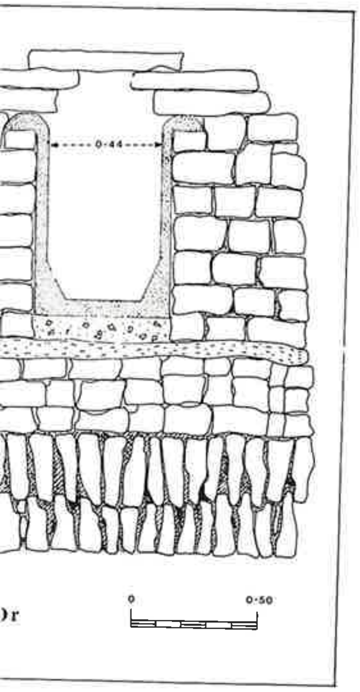

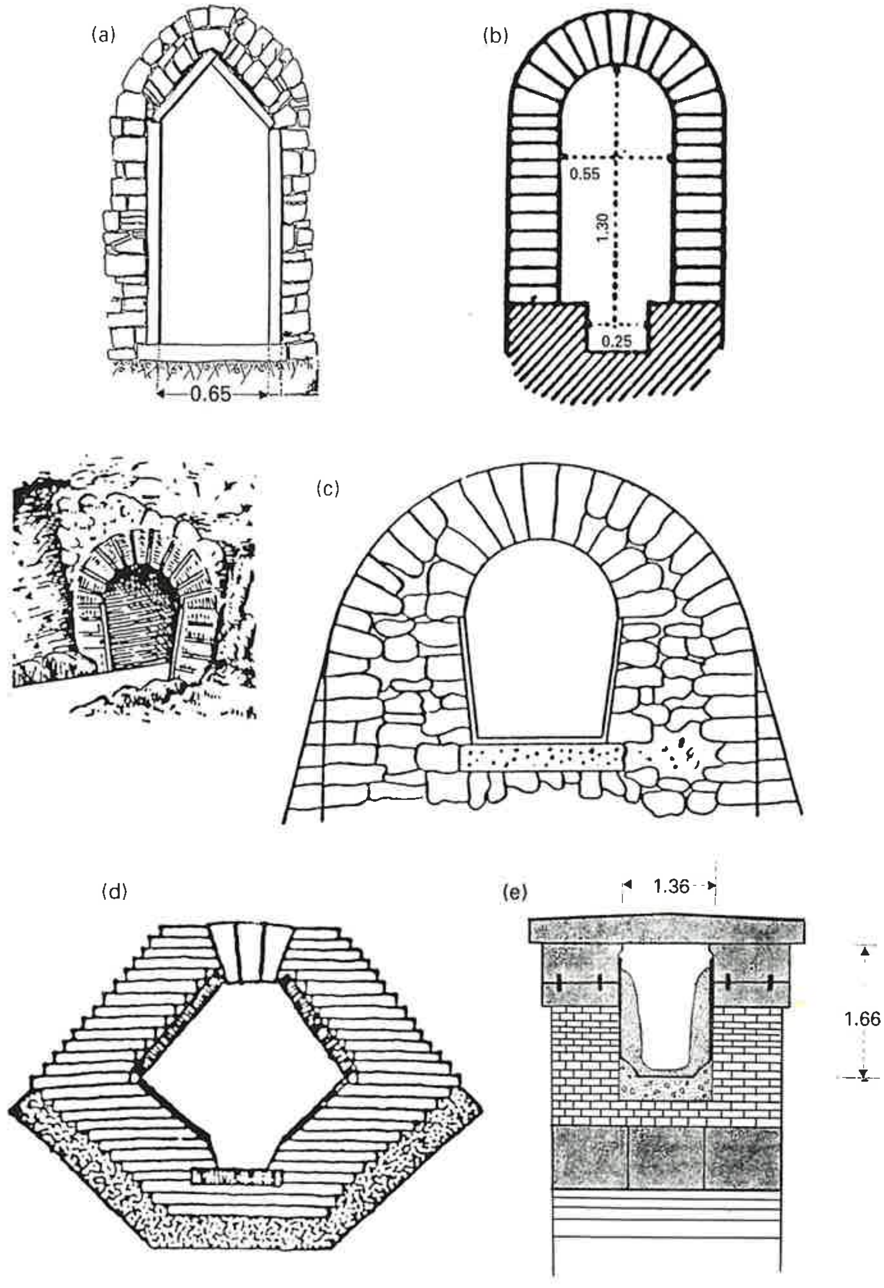

49. Aqueduct channels of various shapes: (a) Ain Ferhat, Algeria: gabled roof; (b) Serino aqueduct, Pompeii and Naples; vaulted roof, with sunken channel in floor to carry the water. The actual water channel is about 0.25 m^2, the rest of the tunnel being to provide access for maintenance; (c) Fréjus: horseshoe-shaped conduit; (d) Alteburg, Rhineland: hexagonal- or diamond-shaped conduit; (e) Pont du Gard, Nîmes: rectangular channel, showing also calcium carbonate deposit.

channel, the cement formed a continuous beading or 'quarter round', as a further reinforcement against cracks developing lengthwise at their vulnerable points.[9]

The function of the cement was threefold: to make the channel impervious to leaks or seepage; to provide a smooth, friction-free contact surface; and to make this surface continuous and uniform with no joints from one end of the aqueduct to the other. As well as performing these functions it also had to be strong and resistant to cracking, whether from heat expansion, freezing, or other causes. Both the composition of the cement and its installation were therefore complex and specialised tasks to which only recently has proper study been devoted. There are three vital features to be noted. First, the material itself is characteristic and easily recognised, looking like either an exceptionally fine concrete or a rather rough-grained cement. It is basically a mixture of quicklime and either sand or crushed brick, looking yellowish or reddish in colour depending on which is used. Second, it is laid in not one, but several layers, like plywood or coats of paint, with pauses between to let it harden; for the whole to set fully took about three months, and probably depended on the weather and season as well.[10]

The number of layers and their composition depended on local needs and circumstances. In the aqueduct of Caesarea (Israel), built around AD 100, Malinowski has identified and analysed no less than six separate layers, forming a total thickness of some 2.6–3.0 cm.[11]

Third, once the last layer has been laid it is carefully rubbed and polished 'to mirror-brightness'. The process as described by Vitruvius refers to stucco applied to the walls of buildings, but something like it seems to have been done to the cement lining of aqueducts. The purpose was threefold. First, as Malinowski points out, this ultra-smooth surface 'inhibits the formation of lime sediments on the walls of cisterns and aqueducts due to a better flow of water. The removal of such sediments during maintenance work is also easier' – that is, it is easier to split off the calcium carbonate incrustation from the channel walls if they are smooth and glossy. Second, this hardens the top layer, which thus acts as a protective skin for those below it. Third, in the rubbing and polishing process the particles of lime and marble assume a horizontal orientation which lends strength to the material and prevents cracking from shrinkage. The full elaboration of this process was not always necessary, because 'for closed canals and tunnels where there is continuous moisture and no danger of cracks caused by shrinkage, the problems were solved in an easier way without such careful polishing'.[12]

On top of the cement lining came the incrustation (Figs 49(e), 159, 160). Not all aqueducts carried this unwelcome addition, for it depended on the quality of the water. The water could carry two kinds of impurities. If it was rather dirty there might be sand, mud or other very small but solid bodies carried along in suspension in the water. The other kind was lime,

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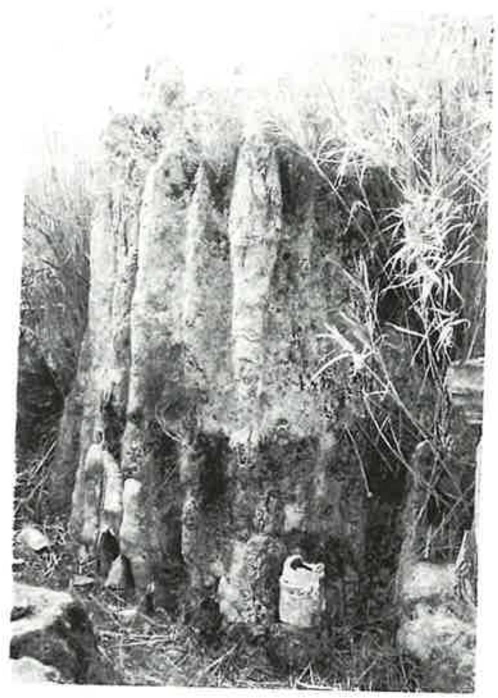
chemically dissolved in the water, and separating out to form a calcium carbonate incrustation on the channels and pipes it flowed through. Water falling as rain is completely pure, so the presence of lime depended on whether it had afterwards percolated through limestone before eventually surfacing in the form of springs to feed the aqueduct. Usually it had, for Roman cities generally seem to have been built in areas where the catchment area was composed primarily of sedimentary rocks, and limestone is indeed retentive of water and hence productive of springs. No geological study of the Roman empire with reference to the hardness of its water has ever been carried out, but the truth is indicated by the end result – heavy incrustation is a standard feature of Roman hydraulics.[13]

This thick lime deposit is itself often built up of clearly discernible layers, not unlike those of the cement liner, except that this time the layering was fortuitous. Should the flow of the water at any time be interrupted and the channel left dry, the exposed surface of the lime deposit would, of course, acquire a skin of weathering. When the flow resumed so would the build-up of incrustation, but with the line between the layers clearly visible. Normally this incrustation dates from the mediaeval period when maintenance and cleaning was at a minimum, and the commonest reason for interruption of the supply was the upheaval of war and siege. It is possible to relate the sequence of layers to the actual historic events that caused them, almost on the principles of dendrochronology, though no one has yet tried to identify and equate a similar sequence of layers in two or more different aqueducts. They are particularly prominent on the aqueduct between the Pont du Gard and Nîmes (Fig. 50).[14]

Whether of layered structure or monolithic, the incrustation could become a serious impediment if allowed to build up long enough. For Aventicum (Switzerland) it has been calculated that with a 3 cm thick incrustation in a channel 24 by 40 cm, discharge was there cut by two-thirds, from 16,600 litres per minute to 5,600.[15] The aqueduct at Nîmes carries an incrustation up to 47 cm thick on the floor and each side of a channel only 1.20 m wide to start with, leaving little more than a narrow slit still clear down the middle. But such a drastic reduction in the aqueduct's capacity did not necessarily reduce the amount of water still coming down from the springs, with the result that at many points along the route it was in a state of copious and permanent overflow (compare Fig. 51 (Perge)).[16]

The build-up of this deposit could only be prevented by chipping it away as it formed, which accordingly became a constant and never-ending duty for the waterworks staff.[17] This is why the channel had to be large enough for human access. In closed lead pipes where no such access was possible this accretion may have been cleared by some sort of pull-through device operating between inspection holes in the pipe (this is commonly done in modern work); or the problem was perhaps simply given up as insoluble

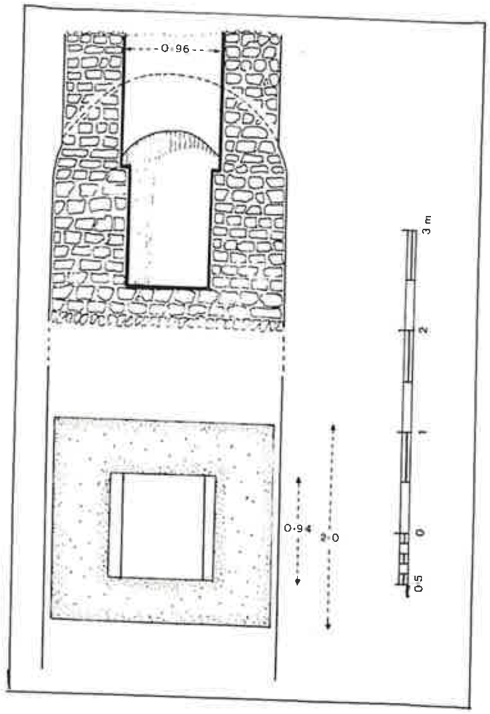
50. Nîmes: edge-on view of the *sinter* (calcium carbonate deposit) accumulated on sidewall (left) of aqueduct conduit, near the Pont du Gard. The sandwich-like layered structure of the accretion is clearly visible.



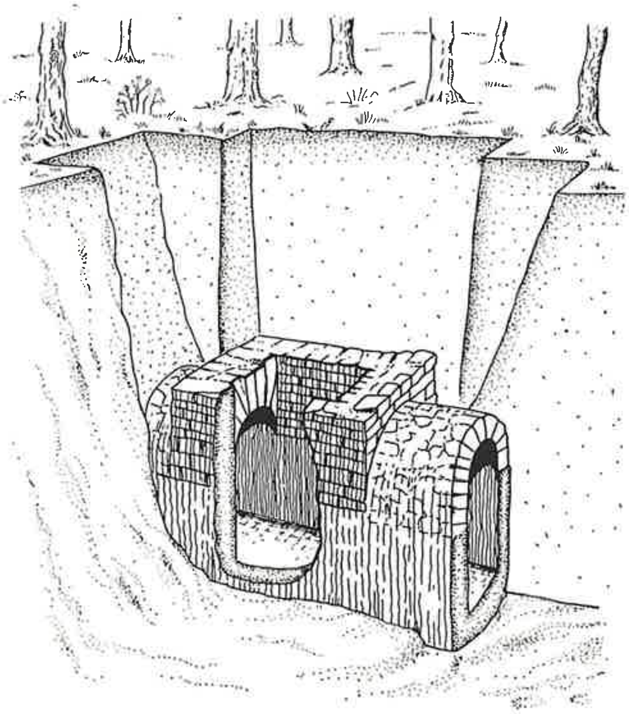
51. Perge: north side of main street: mass of *sinter* formed by overflow from aqueduct. The vertically fluted appearance was caused by the installation of terracotta pipelines to tap the supply; the water, continuing to leak, then led to ridges building up between them, so that when the pipes eventually fell down or were removed (a short section is still visible *in situ*, bottom right), the tracks where they had been remained as open 'flutes'.

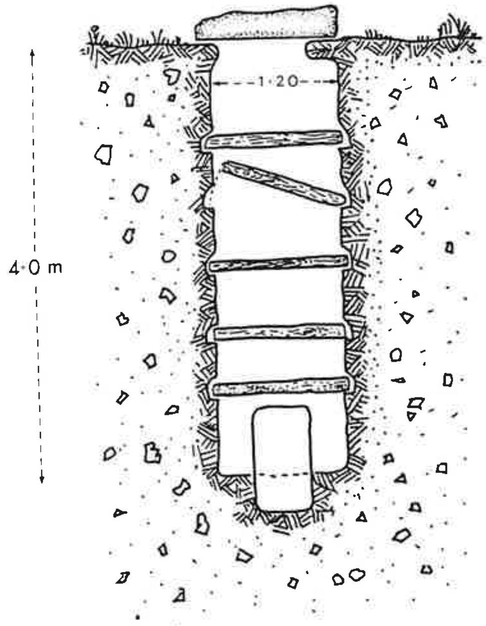
50. Nîmes: edge-on view of the *sinter* (calcium carbonate deposit) accumulated on sidewall (left) of aqueduct conduit, near the Pont du Gard. The sandwich-like layered structure of the accretion is clearly visible.

52. Trier: inspection shaft and manhole (A. Neyses).



53. Cologne: Eifel aqueduct, inspection shaft at Buschhoven (A.T.H., after W. Haberey).





54. Arles: inspection shaft with crossbeams forming access 'ladder' (A.T.H., after Stübinger).

and the pipes completely replaced once they had become fully choked.[18]

When the channel was roofed by flat cover-slabs (see n. 6), these could simply be removed as required, continuously if necessary, to give access for cleaning. When, as was normal, the channel was vaulted on top, access had to be provided by manholes, or, if it was some distance underground, inspection shafts (Figs 46, 52, 53, 54). They are found on the channel of the Carthage aqueduct even where it is running raised above ground, prominently projecting some 70 cm up above the rounded top of the channel like the conning tower of a submarine. Understandably, there is no set distance apart for the manholes (though Vitruvius specifies an interval of one *actus* (= 35 m), VIII, 6, 3), but one usually finds them at intervals of 75 m or so. They often come closer together when there are special circumstances, such as the conduit being on a curve or sunk in a tunnel. Sometimes they were specifically located to facilitate needed repairs.[19]

The openings are usually round, sometimes square (particularly at the bottom of a rock-cut shaft when the channel is in a tunnel); it is not known whether the Romans were influenced by the one great advantage a round manhole has over a square one – it is impossible to drop the lid through the hole.[20]

The manhole was normally fitted with a lid, often in stone (as in Fig. 55). These were very heavy, weighing as much as 300-400 kg and frequently required a crane to lift them. Handles for ordinary manual

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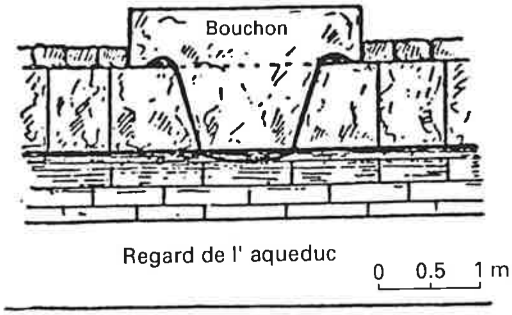


55. Geneva: stone manhole cover, showing tapered fit and recessed handgrips under the edge (L. Blondel).

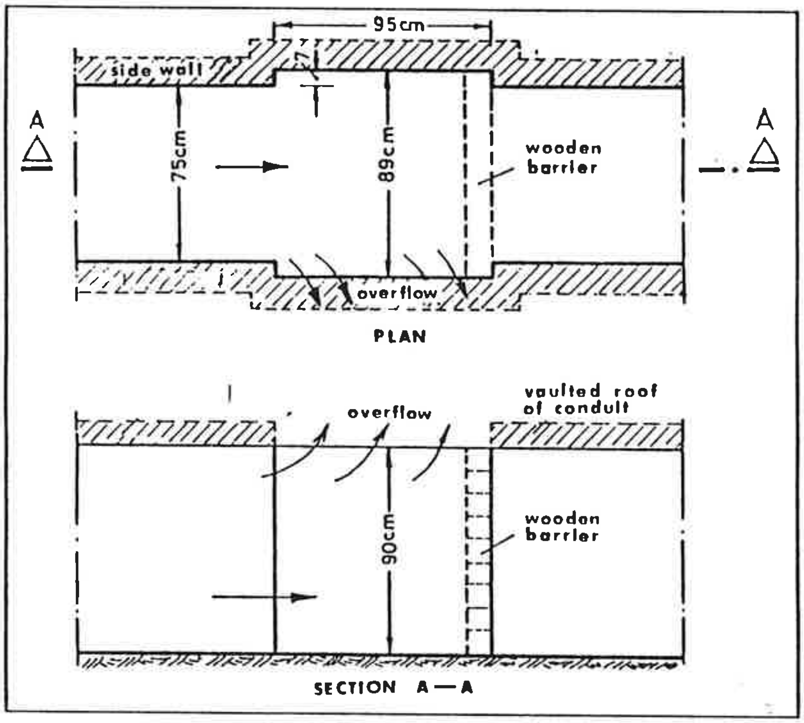
lifting would have been pointless. At Carthage the manholes, now without covering, are reasonably supposed to have had wooden lids, and this may also have been common practice.[21]

The other kind of impurity, sand and the like in suspension in the water, was normally screened out by settling tanks arranged at intervals along the line, which do not concern us here. Sometimes, however, these were supplemented by small settling pits, recesses a foot deep or so and set in the floor of the ordinary channel. They could be round or square and do not seem to have been very common. Examples are preserved on the Brevenne (square; Fig. 57) and at Carthage (round),[22] where they have been explained on the ground that the aqueduct could maintain only a very shallow gradient (actually 1.51 m per km) as it crossed the plain to the city of Carthage, and sediment accordingly would be very prone to settle on the bottom of the conduit because of the low velocity of the water. The presence of such settling pits would, by itself, require close and convenient access by manhole for the removal of the accumulated sediments.

Alongside the aqueduct channel its course might be marked by *cippi*, usually about 71.3 m (=240 Roman feet) apart. A *cippus* (literally 'a gravestone') was a small stone marker set into the ground, and 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 particular section of the line. They might also indicate the limits of the dedicated right-of-way through which the aqueduct ran, and upon which encroachments by neighbouring proprietors were prohibited.[23]

Cippi seem to be found only on the aqueducts of Rome, and not on all of them. They were apparently instituted by Augustus, who installed them on existing aqueducts such as the Marcia and the Anio Vetus, which had previously lacked them, as well as on new construction and renovation.[24]

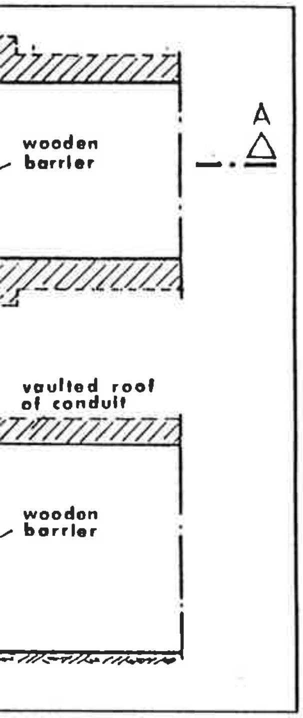
However, though the *cippi* gave an easy framework of reference, it looks as if it was not actually much used. Frontinus, no doubt following the common practice in the water office, regularly describes any location on the aqueduct line, not by its *cippus* number, but by the corresponding



56. Lyon: overflow chamber on Gier aqueduct. When the ongoing channel (right) was shut off by the wooden barrier of stoplogs, the water was diverted to overflow through the opening in the roof and upper sidewall of the conduit (Jeancolas, 1978).

milestone on the nearest main road.[25] This was not as unlikely as it sounds, for roads and aqueducts often paralleled each other and the road was in any case the normal route of access for the maintenance crews and the milestones on it their accustomed point of reference. At Rome, moreover, roads and aqueducts had originally been under the charge of the same magistrates (the censors or aediles).[26] Where no road was convenient, a service road might be built alongside.[27]

The final point to be noted about our typical section of aqueduct is that it is probably running at right angles across a hillside. Aqueducts tend to be built through the hills, and not just because of the traditional purity of mountain springs. This is in fact true, but more important than purity is height. The water had to be brought in at a level high enough to serve all parts of the city. This was always liable to cause problems, particularly where the city had some kind of an acropolis, such as the Palatine and Capitol at Rome or the heights of Fourvière that formed the core of ancient Lyon, and it usually meant that water had to be sought from a source in the hills even if there was an adequate, but lower, one closer at hand. During its passage through the hills the line of the aqueduct



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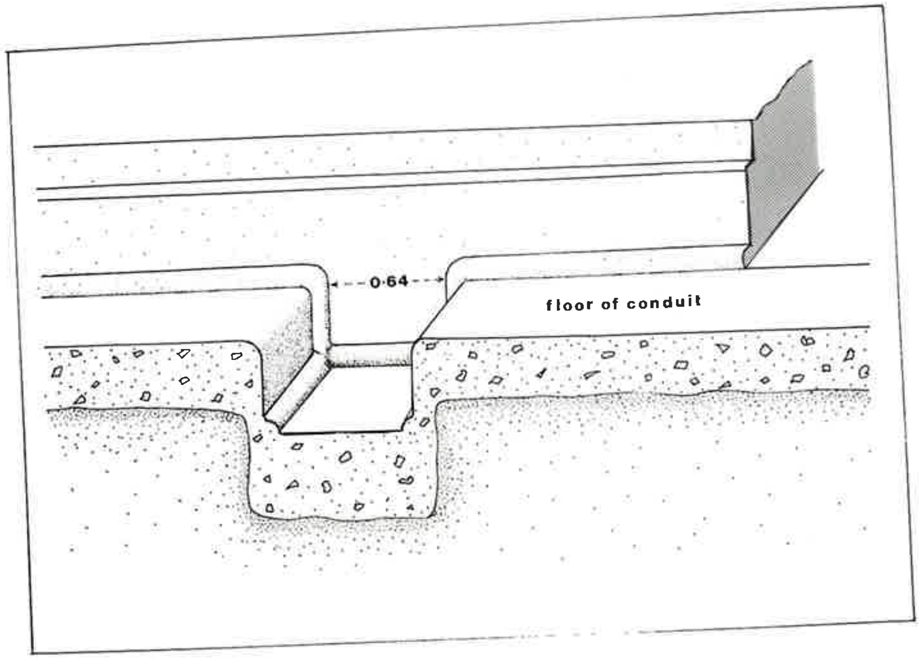

57. Lyon: settling basin set into floor of aqueduct channel at Sotizon, La Brevenne aqueduct (A.T.H., after Cl. Lutrin).

normally remained level so far as was possible (if we neglect the slight slope required to maintain gravity flow), like a canal or a contour line on a map. Therefore, just because it did more or less follow the contour lines, so did it usually have the land higher on one side than the other. Typically, this led to trouble, for the masonry conduit, submerged perhaps a metre or so below ground level, was liable to act as a kind of underground dam, a continuous concrete wall some two metres or so high, against which rainwater, percolating downhill through the topsoil, would accumulate. A conduit was therefore liable to be accompanied on its uphill side by a continuous band of heavily sodden earth, the water coming not from leakage out of the conduit but from surface water outside. In winter this was then liable to freeze (since, unlike the water in the aqueduct, it was not moving), cracking the conduit. The problem could be solved by providing adequate drainage (at Cologne there was a drainage canal running parallel to the aqueduct and slightly uphill from it), but this was not always done.[28]

Other forms of conduit

The open channel

The masonry conduit just described is by far the commonest form that

Roman aqueducts take, but there are five other possibilities that must be mentioned. The closest is the stone-cut channel and its earthen equivalent, the open clay-lined leet. The other four are pipes, of various materials, which therefore present rather different problems.

That the normal aqueduct channel should sometimes become rock-cut whenever rock was encountered in its path goes without saying. If underground, it then might or might not be also masonry-lined. Minor aqueducts, 'particularly in mountainous or sparsely inhabited country',[29] or those for agricultural or industrial (as opposed to urban) use, often followed this pattern, running in a rock cutting where necessary, and otherwise in a dug channel, like a stream, across the fields. Like streams, and unlike the upright, oblong cross-section of the masonry conduits just studied, they were usually squarish in section, or even wider than they were deep, and the water was liable to fill only part of the channel.[30] It seems unlikely (though not really known) that they were continuously covered over, but attempts could be made (apart from the usual settling tanks) to minimise sand, earth and other impurities getting into the stream by lining the banks with clay and the bottom with 'stretches of smooth laid stones'.[31]

On hillsides, if rocky, the channel could be formed by cutting back the rock on the uphill side and forming the downhill side of the channel by building a continuous masonry wall, or sometimes insetting vertical cut stone slabs (compare Figs 58, 59). On an earthen slope the same revetting effect could be achieved by shoring the channel up on one side with wooden planking. Streams or small gullies could be crossed by carrying the water across in a wooden trough supported by trestles, or even, if the supply was small enough, in wooden pipes made of hollowed-out trees.[32]

It may well be that on some of these small aqueducts (particularly in Mediterranean and North African lands where flash floods are common) stream or wadi crossings were often formed of some temporary wooden structure deliberately regarded as disposable and provided in the full expectation that it might be swept away by the spring or autumn rains and have to be replaced as a matter of course.[33]

Many of these industrial and irrigation aqueducts were no doubt small and minor in scope – some modern equivalents in the *falaj* of Oman are illustrated in Costa's article (n. 32 above) – but industrial needs could be quite extensive. The Dolaucothi aqueduct was in places 1.5 m or so wide, and carried a volume of water roughly equivalent to the Aqua Alsietina at Rome. Despite its industrial purpose, some importance was also attached to purity, hence the stone or clay lining and settling tanks.[34]

Pipes

Pipes can be made of terracotta (earthenware), lead, wood and stone. The use of all four is attested in Roman aqueducts, though in differing er possibilities that must be channel and its earthen er four are pipes, of various erent problems.

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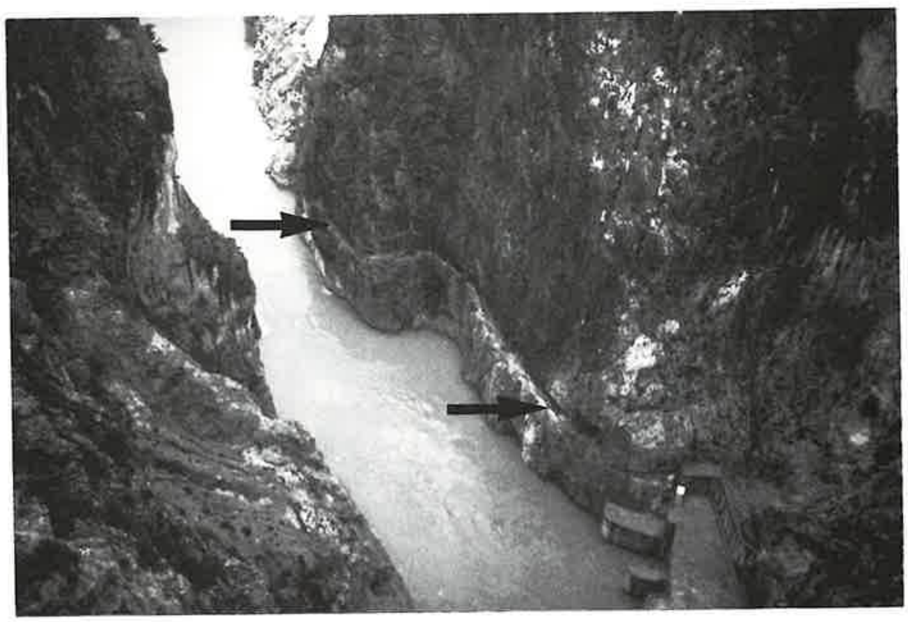
58. Side, Turkey: rock-cut channel of the aqueduct (photo: H. Fahlbusch).

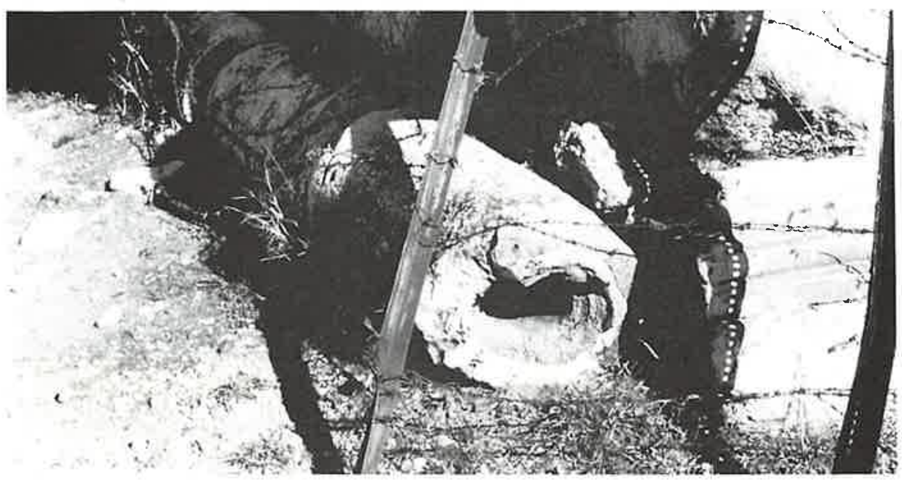


59. Side, Turkey: rock-cut channel carrying the Roman aqueduct (indicated by arrows) along the gorge of the river Manavgat, immediately below the modern dam.

60. Hammat Gader (Golan), Israel: stone pressure pipe in the Roman Baths.

61. Miletos, near the Agora: block from stone pipeline, with right-angle bend.

62. Side, Turkey: length of round stone pressure pipeline *in situ* (?) facing the theatre, carrying inside it a heavy incrustation of *sinter* (3-8 cm thick).



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63. Segovia: re-used block from a stone pressure pipeline (arrow) embedded in the arches of the Roman aqueduct.

64. Mainz: typical length of wooden pipe (courtesy C. von Kaphengst).

65. Aachen: Roman wooden pipes, showing (centre) metal collar (photo: K. Grewe, Bonn).

amounts and varying circumstances. There is no evidence for bronze pipes, other than the adjutages (*calices*) at the offtake points of urban domestic lines, and the long-standing suggestion that the Pergamon siphon was laid with bronze pipes, apparently based on nothing more than conjecture but still repeated in some works, is now known to be wrong: the pipes at Pergamon were of lead.[35] Despite Vitruvius' suggestions, on the country aqueducts lead pipes were used only for siphons, where metal pipes were needed to withstand the pressure generated. In the city distribution network, on the other hand, they were the standard thing and will be discussed in Chapter 10.

Stone pipes also occur, and they are not as rare as used to be thought. Usually they are of large size, for the main aqueduct rather than the various small-gauge branches of the distribution network, and normally consist of a series of stone cubes each bored through with a round hole, which fitted together so as to form a continuous tube, while externally looking like a course of squared ashlars; sometimes, however, these outer surfaces have been left rough (Figs 17, 60). The joints were shaped to fit together on the male/female principle, much like the ends of terracotta pipes to be discussed below, and once one knows what to look for, it is not uncommon to find individual blocks of this sort lying around sites where a stone pipeline has not been published or otherwise attested. Their commonest use seems to have been in siphons (for which see pp. 33-41 above), but they were also found in other positions (such as some of the internal city mains) where the water ran under pressure, even low or nominal pressure (Figs 11, 61). Special blocks incorporating a right-angle elbow joint or T-junction are relatively common, as are those featuring vertical 'vent-holes' – the inverted commas are advisable, as their actual function, to me at least, remains uncertain.[36] Round stone pipes (instead of the cubical format) are rare but do occur (Fig. 62), though one must here, if possible, be careful not to confuse them with the round stone sleeves ('*marmormuffen*') sometimes used, as at Ephesos, to accommodate the joints on a pipeline otherwise made of lead; similar isolated stone blocks sometimes occur at bends.[37]

These stone pipelines are particularly numerous in Turkey and the Middle East, though examples do occur in Italy, North Africa, and even as far west as Baelo (ancient Bolonia), near Cadiz on the Atlantic coast of Spain; and what looks like a re-used block formerly associated with such a pipeline is even to be found embedded in the arches of the aqueduct at Segovia (Fig. 63). The best known, and most accessible, such pipleine is the siphon at Aspendos (which ran in a single stone pipe), but the best preserved are probably those at Patara and Laodicea: the Patara pipeline exists almost in its entirety (Fig. 12), and at Laodicea there is a section of over 25 blocks still *in situ* and all joined together. As previously noted, the dating of these stone pipelines, whether in siphons or not, is unclear. Traditionally they have always been considered Hellenistic (at least the

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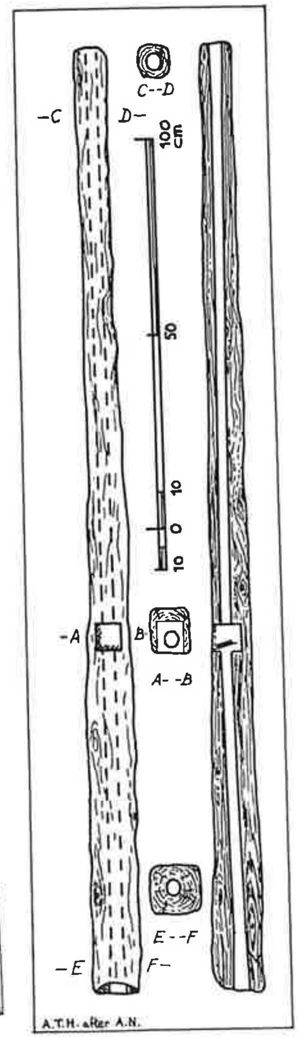
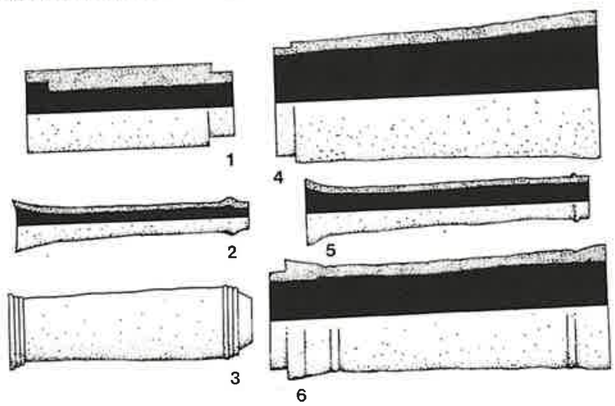


66. Wooden pipe hollowed from tree-trunk, with square access hole on top (to assist cleaning?) (A. Neyses).



67. Terracotta pipes: various forms, from (1) Nemi; (2) Wiesbaden (mediaeval?); (3) Worms; (4) Strasbourg; (5) Jagsthausen; (6) Mainz (Samesreuther).

ones in the east), but a stone pipeline is in itself not intrinsically an easy thing to date, and it now appears that they may all be Roman work.[38]

Wooden pipes, which were again much more used for urban networks than the main aqueducts, but were common in small isolated systems individually supplying villas, forts and the like, were particularly numerous in northern Europe, especially Germany (Figs 64, 65). In Britain they replaced lead piping as the normal practice and at Caerwent were even used in a siphon, where several of them burst under the pressure and were repaired with small lead patches. In spite of a common belief that 'wood rots and splits', this is in fact incorrect. Wooden pipes do not decay as long as the wood remains constantly wet, and it is only an

68. Ephesos: a stack of terracotta pipe sections of different kinds; apart from size, differences include presence or absence of internal *sinter*, and varying thickness of sidewalls, depending on whether they were intended to be subjected to pressure.

alternation of wet and dry that causes rot to set in.[39] A wooden pipeline normally consisted of tree-trunks with a hole bored longitudinally down the middle (Figs 64, 66). This ensured an actual water channel of neat, uniform cylindrical bore, but an irregular exterior as the trunks were usually only roughly trimmed and always retained, from the natural profile of the tree, one large end and one small. The joints were normally reinforced with circular iron collars, which have often survived as the only evidence for the aqueduct. At Caerwent a series of collars was found *in situ*, alternately of three inches and four inches diameter, indicating that here the sections of piping were regularly laid in pairs, with the two large ends together, and the two small ones likewise. This would of course facilitate the jointing, and we may presume that such a sequence was common if not invariable practice. The pipes (or trunks) were most commonly made of oak (Pliny, *NH* XVI, 81, also recommends pine, pitch-pine, and alder),[40] and come in lengths varying from around 1.5 to 7.5 m; the hole for the water could be from 5 to 10 cm in diameter. The whole pipeline might then be embedded in packed clay, with supporting stone slabs set under the joints. Internal cleaning might be difficult, but we sometimes find wooden manholes or access shafts, so that a cleaning device could be pulled through the pipeline, or its contents and condition at least inspected.[41]

The advantage of wooden pipes was of course cheapness and in Northern Europe ready availability. Trees did not come in standard sizes the way lengths of lead piping did, nor did the bored holes always match

69. Ephesos: terracotta pipelines beside the Library of Celsus. The various sections are of differing size (note the small one to the left end of the upper pipe), showing that these pipelines are late work, made of re-used materials.

the various gauges of pipe so rigidly specified by Frontinus, but this was not a problem that affected small, self-contained aqueducts where the question of drawing a prescribed amount of water from a larger system did not arise.

Another advantage was the length of the sections, reducing labour costs on the joints (this must have been a considerable factor *vis-à-vis* the very short lengths used in most terracotta conduits, as we shall see). Of course, the use of long, straight sections also brings a loss of flexibility in laying out the line of the aqueduct, and to follow a serpentine course the smaller terracotta sections would presumably be more suitable. Samesreuther also maintains that a wood surface reduces friction on the water-flow, accelerating the velocity.[42]

Terracotta pipes (Figs 67, 68, 69), after a masonry channel, were the commonest form for an aqueduct to take. They are found both in some of the smaller main-line aqueducts and in local urban distribution systems, to say nothing of drains. Contrary to traditional belief, they were also sometimes used for pressure lines (identifiable when one notes that the pipe walls are exceptionally thick relative to its diameter). They were the one all-purpose form of conduit, and in a study such as this it is hard to know where they would most appropriately be considered.[43]

The individual sections are normally around 40-70 cm long and with an internal diameter of up to 10 or 15 cm. The length was presumably often limited by their having been thrown on a potter's wheel, nor were they usually completely cylindrical, for the joint was usually effected by having one end slightly narrower so that it could slide inside its larger neighbour (with an appropriate flange or groove to help seal the joint).

70. Mt Beuvray, France: pipeline made of re-used amphorae, with tops and bottoms removed so that they fit into each other. Photograph by the excavator, J. Délechette, in 1907) (photo © Beuvray).

Though this need not have affected the internal diameter, in fact it usually did, and a terracotta conduit seldom has a completely parallel internal bore. We may also in passing note (Fig. 70) a unique curiosity from the Gallo-Roman site of Bibracte (Mont Beuvray, near Autun, Burgundy), which boasted a pipeline made entirely of re-used wine amphorae, their tops and bottoms knocked off so that they fitted snugly into each other at the joints.[44] I know of no parallel to this. The short length of terracotta pipes meant a very large number of joints – the terracotta pipelines of the Pergamon aqueduct had 200,000 of them and used so many pipe-sections that they were evidently manufactured not only on the site but at several different locations along the aqueduct, as attested by differences in the clay.[45] Terracotta pipes are also often provided with an opening on top, covered by a removable lid. The purpose of this may be simply to facilitate cleaning; its effect is clearly to destroy any possible claim that this be considered a pressure pipeline: once the pipe ran full, plainly the water would begin overflowing through the holes along the top, so that a pipe constructed in this way must be thought of as operating on the same general principles as an open channel under gravity flow. Sometimes every single section of pipe has an opening and it is plain that in this case the intention was to enable the workman to get his hand into the pipe to plaster from the inside the joint with its neighbour.[46]

The joints were fitted into each other and sealed with a plaster, in composition somewhat like the waterproof cement lining of masonry channels. This has again been studied and reproduced by Malinowski. Its basic ingredient was quicklime, *calx viva*, from which was produced an ' "expanding rim" sealant'.[47]

Pipes: the line of the aqueduct

Although it was not common for the Romans to follow Vitruvius' suggestion and actually build an aqueduct carried in pipes throughout, it did occur. The use of pipes entailed a radically different approach to the routing of the aqueduct. Unlike the normal masonry channel, which was designed to run only half-full and under gravity flow, pipes, except where their integrity was destroyed by inspection openings on the top as just mentioned, were intended to run full. This in turn means that a pipeline would run under at least nominal pressure. We are not here speaking of the high pressures generated in a siphon or any of the other locations that have so worried modern commentators. All that is meant is that, unlike an open channel, a pipe need be laid only roughly level. Minor bumps and dips in the line are of no importance. The water will surmount them without trouble, so long as the general tendency of the line is gently downhill, and though this will inevitably cause some changes in pressure within the pipes, the changes will be so small and the pressure so low as to be insignificant and easily contained both by terracotta pipes and even their plastered joints. In theory, this means that a pipeline is probably easier to lay out than a conventional channel. For there is a much greater tolerance in establishing the level, nor are the results of an error so drastic; 50 cm too high could result in an aqueduct overflowing and the rest of the channel running dry, but could be accommodated in a pipeline. A pipeline would also certainly be shorter for it need not adhere so slavishly to the contour. It can cut corners, and its course need not be so serpentine – it is rather like the difference between building a railway and a canal. This does not mean, of course, that the pipeline followed a straight line with all the pressures and/or engineering works involved, only that it was more flexible than the orthodox channel. The disadvantage of a pipeline was its small capacity, as compared with a masonry channel. This meant two things – that, the size of pipes being limited, they were often laid in groups of two or three (on the analogy of lead siphon pipes, which were often laid in batteries of up to nine); and that their use was normally restricted to small aqueducts.

It must also be admitted that this issue is not nearly as clear-cut as it might appear, for discharge through a pipe depends on velocity, which itself varies with circumstances, and these circumstances varied much more with a pipeline, which might be running under a head of pressure varying at different points along it, than with a conventional channel running under more or less uniform gravity flow. The point is well

71. Caesarea, Israel: 'flat' siphon on north aqueduct, with three terracotta pipes laid in the bottom of the open conduit they replaced.

demonstrated by the Hellenistic aqueduct of Pergamon which, on the main section of its course from the springs at Madradag to the settling tank at Haghios Georgios, ran through an orthodox, unpressurised, set of three terracotta pipes (16-19 cm inner diameter). From the settling tank on, the aqueduct went into a siphon, in which one single pipe of similar dimensions (actually 22 cm) apparently handled all the water delivered by the other three. There is no sign of any other offtake or overflow at the tank, and theoretical calculations have confirmed that the flow-capacity of the triple-pipe conduit and the single pipe siphon are in fact the same.[48]

Probably the best example of a line entirely laid with terracotta pipes is the Kuttolsheim aqueduct, serving Strasbourg.[49] It was 20 km long and laid with a pair of terracotta pipes, 30 cm in diameter, running side by side and usually about 1 m deep in the ground, an adequate protection against frost in these northern regions. It is described as having 'une pente variable mais continue' and, where necessary, crosses depressions not on a built masonry *substructio* of the familiar type, but on an earthen embankment created by digging a pair of ditches parallel to the desired alignment, one on either side, and heaping up the excavated material in the middle. The 'pente variable mais continue' is exactly the kind of arrangement that can be accommodated by pipes but which might present difficulties in an open channel, making this a good example of a simple aqueduct, unambitious in scope but efficiently engineered.

Another possibility is the use of pipes to replace a section of aqueduct channel that, for one reason or another, had become unserviceable. This seems to have happened at Lyon and also at Caesarea Maritima in Israel, where at some time a stretch of the aqueduct, here running on arches, was replaced by three earthenware pipes (17 cm in diameter), running along the actual bottom of the open channel and embedded in a mixture of mortar and small stones (Fig. 71). They reduced the carrying capacity of the aqueduct by 90 per cent – from 38,400 m^3 per day to 3,600 – and it is suggested that the substitution was required because of subsidence: the aqueduct structure sank in the soft ground, leading the water to overflow and cut off supplies to the channel on beyond. The replacement by pipes turned this section, in effect, into a long and very shallow siphon, and no doubt 3,600 m^3 was much better than none at all. It puts it, after all, into the same general range as the Pergamon siphon. We may also note in passing that at at least two points this siphon was interrupted by being 'brought up for air', to a surface level tank (see Figs 170, 171 below) after the fashion of Les Tourillons, on the Craponne aqueduct.[50]

Curves, junctions and settling tanks

As it followed the contours through broken terrain, the line of the aqueduct often developed an extremely sinuous course, as sinuous as the contours themselves. The greatly increased distance made no difference to discharge or real efficiency in the aqueduct, for the longer time the water took in getting to its destination was plainly of no importance to anyone; but it made an enormous difference to maintenance costs, both of the perennial task of cleaning the channel free of incrustation, and of repairing cracks, leaks and even landslides. The increased length could also bring down the aqueduct gradient below acceptable levels, resulting in stagnation of the water. These provisos apart, Roman aqueducts often do meander (in striking contrast to Roman roads), entailing plenty of gentle sweeping curves.

Sudden abrupt curves, sharp angles and acute bends, one thinks, might be a different matter. Would it not assist the flow to have the course streamlined? In fact, abrupt bends are a rarity in piped supplies. Terracotta pipes in the form of a right-angled elbow bend have rarely been found, and the more common technique was to achieve the more gentle sweeping curves mentioned above by laying short, straight pipes, with the curve being taken up in the joints. Another procedure occasionally used to negotiate a corner was to instal at it a large, round *pithos* or other jar, with the terracotta pipeline emptying into it through a hole in one side, and leaving by another offtake pipe cemented into the jar at right angles. The jar thus served both to eliminate inertial thrust as the current rounded the bend, and as a silt trap, the accumulated debris being removed through its open mouth.[51] Another possibility was to

72. Miletos: stone angle block *in situ* at bend on terracotta pipeline.

introduce at a bend on a terracotta or lead pipeline a single, isolated stone block pierced with an L-shaped hole. The bend was thus contained entirely inside the block, which provided the requisite strength to resist the centrifugal thrust as the water negotiated it (Fig. 72).

But the conventional masonry or rock-cut channel was a different matter. There was no reluctance to build or cut a channel to form an abrupt angle – even right angles are not rare – and that often where it would have been quite simple to introduce a curve into the line, at least for a metre or so on either side, to ease the current into its change of direction.[52] One often finds them at one end (or both) of an aqueduct bridge where the conduit, running along one side of the valley, goes round a sharp corner to continue out on to the arches.[53]

Sometimes the bridge is a later addition to cut off a circuitous loop in the line; it is then liable to form a T-junction at each end where it leaves and rejoins the original line, and if half of the T (the abandoned loop) is then blocked up, one has a right-angled bend even if this was not in the original design. This happened at Cherchel, and one may see something like it at Saintes.[54]

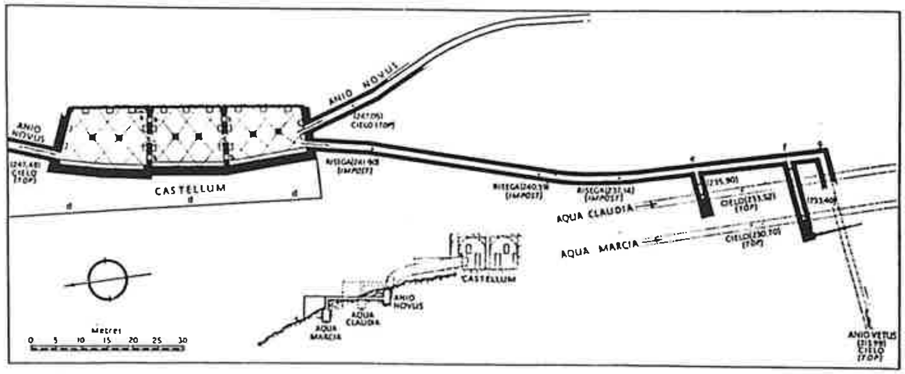
It also sometimes became necessary to introduce a bend in the middle of an aqueduct bridge or arcade, and here again the bend is usually an abrupt one, though it would have been easy enough to build the arches in a curve. On such occasions the Romans may have been aware of the consequent sideways thrust on the masonry structure at this bend – at Aspendos they strengthened it with buttresses, at Segovia (Fig. 73), in similar circumstances (but with a very small conduit), they did not.[55]

Irrespective of the effect on the bridge structure, however, there cannot be much doubt about its effect on the water flow. These sharp angles, if

73. Segovia: angle in the arcade. There are no buttresses to counter centrifugal force at the bend.

the current was running fast, must have created considerable turbulence and acted as something of an obstruction. The Romans apparently did not mind, perhaps rightly. Uniformity of flow was never attained anyway in a Roman aqueduct, but will 'always be in a state of change, trying to adapt to the new conditions'.[56] To put it another way, obstructions in the way of changes of channel width and gradient abounded, so that the current was always either being already affected by the next one to come, or still recovering from the last one. The turbulence created by right-angled elbow bends may therefore be less important than one would think.

In the open country (as opposed to the city *castella*), junctions occur when additional channels join the main line[57] of the aqueduct as tributaries, sometimes added later to increase the discharge; and where branches leave it to serve other locations. To generalise, the first are most numerous near the beginning of the channel, in terrain where there are other springs to be tapped. The second usually occur on or shortly before arrival at the city, where there are other suburbs to be supplied. On the middle section of an aqueduct – one might say the middle 80 per cent of its length – junctions of either kind are rare. Once it has collected all possible water from local springs, and until it reaches the urban area, the aqueduct usually runs through as a single line, so junctions do not arise. When they do, they are of two different kinds. First, the two channels, whether masonry or piped, may join directly in a T or Y-junction. Second, without actually joining, they can be arranged both to empty

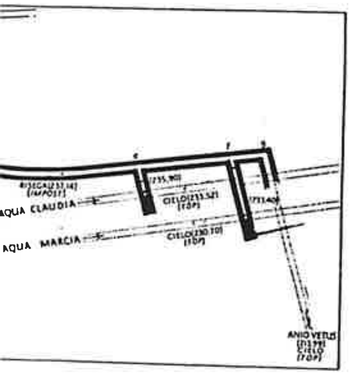


74. Rome: Grotte Sconce, a settling tank and junction chamber on the Anio Novus, showing crossover link for diverting water down into the Marcia and Claudia (Ashby).

independently into some large reservoir or receptacle, in the other side of which is the offtake for the continuing main line of the aqueduct.

To consider first junctions of the direct type, few if any of these are to be found on piped aqueducts. They are common enough on pipes of the street or urban distribution systems, and will be considered there. By direct junctions in conventional masonry channels, I refer to Y or T-junctions where one channel simply runs straight into the other, such as at Osteriola junction on the Anio Novus. At such a junction each of the incoming lines may also be fitted with a small clearing tank just before the junction point. Other more complicated forms of junctions are found when it is a question of putting in some sort of cross-link from one aqueduct to another, at a point where they run nearby, to enable water to be diverted. The complication comes from the fact that the two channels are hardly ever at the same level (which means that flow through the link is not reversible, and it is only the upper aqueduct that can feed the lower), resulting in arrangements such as we see at Grotte Sconce (Fig. 74) and S. Cosimato on the Rome system. At the first, a pair of cross-links from the Anio Novus supplied the lower-lying Claudia and Marcia, in each case apparently joining them by coming in vertically through the roof. At S. Cosimato, the Claudia passed directly above the Marcia and the two were joined by a vertical shaft, opening apparently out of the side of the Claudia and regulated there by a sluicegate, and falling straight down and into the Marcia through the roof. This shaft, or *puteus*, on the Marcia, which was built first, was 1.2 by 1.08 m, and some 9.2 m deep (Fig. 75); the water thundering down it must have been an impressive sight when it was in operation.[58]

Indirect junctions on piped aqueducts usually take the form of some sort of small box into which the ends of the pipes are introduced.[59] In orthodox channels the junction can take the form of a large reservoir,



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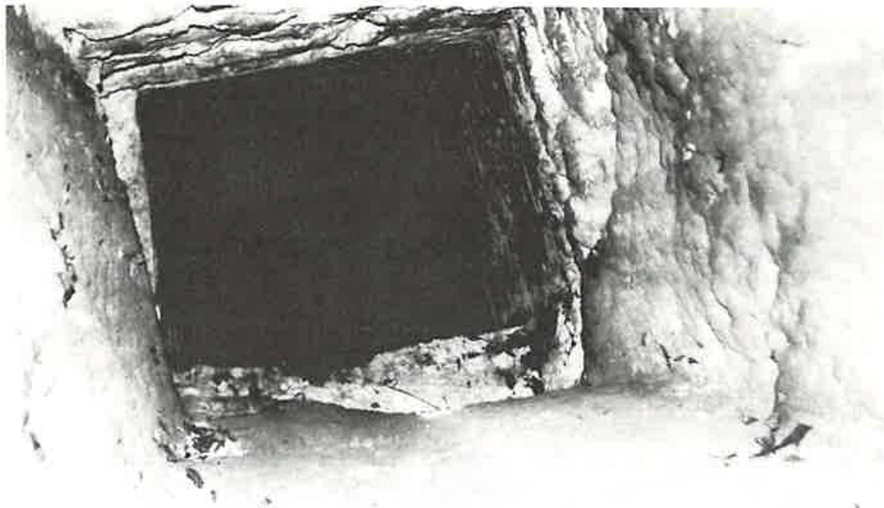
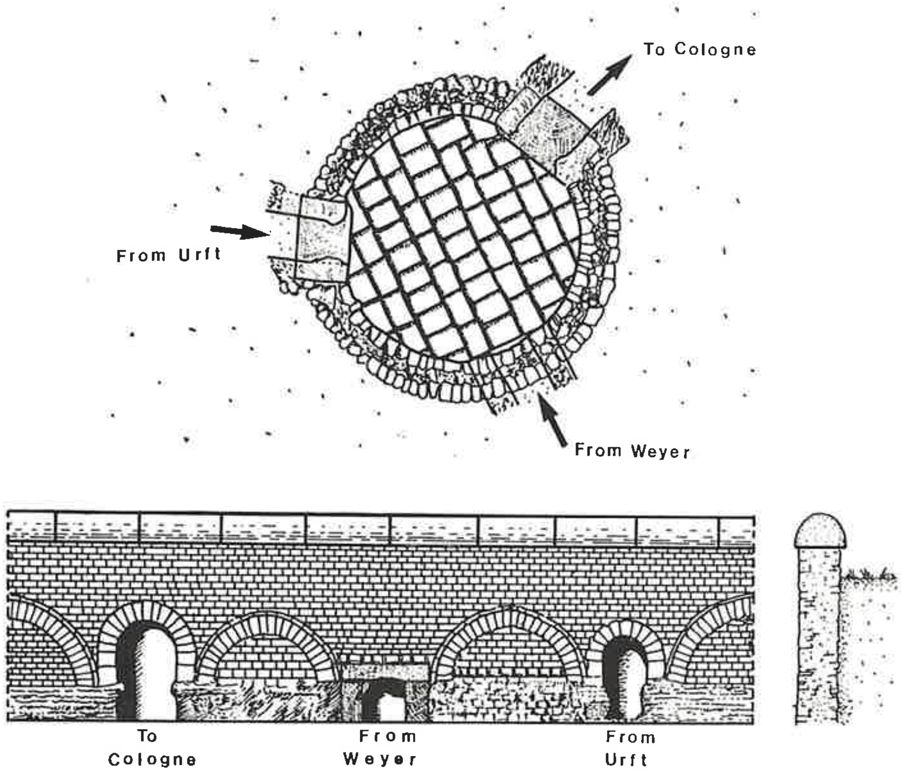


75. Rome, Aqua Marcia: view directly up the vertical shaft at S. Cosimato, through the roof of the Marcia channel to the channel of the Claudia, 9.20 m above.

rather after the fashion of a *castellum divisorium*, with the various channels entering or leaving it as required. It may also double as a settling tank. Thus at Grotte Sconce the Anio Novus entered a large triple-chamber vaulted reservoir, from which were led off the cross-link channels to the Claudia and Marcia just mentioned:[60] from the opposite corner left the Anio Novus, continuing on its way, but dropping 0.43 m in level as it left. The water of the Anio Novus was notoriously sandy, and no doubt this reservoir constituted an attempt to get rid of as much of the impurities as possible before (when this was necessary) diverting them into the purer waters of the Marcia and Claudia, so that this constituted both a junction and a settling tank combined and conceived to serve a single purpose (as well as achieving a drop in level). An analogous arrangement can be seen at Grüngürtl on the earlier Cologne aqueduct. A junction here being necessary, the opportunity was seized to combine it with two large settling chambers, a complex array of regulatory sluices, and a drop in level of 2.1 m, this time only on the branch line.[61]

A simpler and no doubt commoner layout is to be seen, also on the Cologne system, at Eiserfey junction on the Eifel line (Fig. 76). This is a shallow, circular open tank of 3.05 m in diameter, its paved bottom 2 m below ground level. As restored, it is surrounded by a low guard wall with a sandstone coping, and much resembles the well known *castellum* at Nîmes. At floor level the main aqueduct from Urft, running in a vaulted masonry conduit just below ground, enters through an arched opening and leaves through a similar but larger one on the other side on its way to



76. Cologne: Eifel aqueduct, Eiserfey junction chamber and settling tank. Above, plan: the main line of the aqueduct arrives (left) from Urft and continues on to Cologne (top right). At the bottom a branch line from Weyer, running in a much smaller tunnel, joins in. Below, restored elevation. The whole tank was open to the air (W. Haberey).

Cologne. Between them a short tributary branch from Weyer enters through a small square aperture. The three channels are spaced at equal distances around the circumference of the reservoir, and enter and leave it flush with floor level so that there is no question of this having been intended as a settling tank. Its function was presumably threefold: to effect a junction conveniently and in a manner avoiding, so far as possible, excessive turbulence at this confluence, which could harm the conduit lining; to give ready access for inspection and maintenance at a key location in the network; and to provide an impressive public display. This last hypothesis rests on the tank being open to the sky, and hence to view; the whole appearance suggests a place of public visit and resort (as was the Nîmes *castellum*), although it was of course in the open country and not an urban setting as at Nîmes. It may also have been used as a convenient place for drawing water.[62]

It may well be that something like this was the commonest form of indirect junction, where such was used, but the evidence is really very thin. Usually actual junctions on aqueducts are either not preserved or not identified and excavated, and their existence rests on purely topographical evidence: that is, enough is preserved of the two channels to give the alignment and it is known that they must have joined somewhere, but the location of the junction is conjectural; so, therefore, is its form.[63]

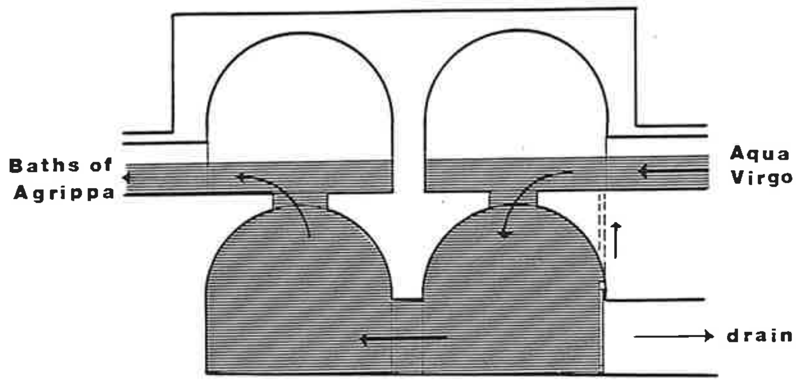
Settling tanks were also found along the main stretches of the aqueduct, though, like junctions, they occurred more often near the beginning, to clear the water on leaving the springs, or near the terminal *castellum* and the urban network.

On the short (8.5 km) aqueduct at Siga (Algeria) there was a series of at least twenty small basins (some oval, some round, and of about 1 m^3 capacity). Each was located not on the aqueduct line but close beside it. Water was brought into the basin by a short connecting channel, and left it by a second one, at right angles, back into the aqueduct, so that the basin was situated on a sort of loopline or by-pass.[64] Was this a settling basin or an access point from which local farmers could draw water? We cannot tell, and hopes must rest on finding a similar installation elsewhere that will throw light on the matter.

Large settling tanks are both rarer and more common – rare because any given aqueduct will have only a few of them as compared with the twenty basins at Siga, more common because plenty of aqueducts do have them, while the Siga arrangement remains unique. Again their function is not wholly clear. A good example of such a circular tank has been found at St Cyr, near Lyon; it is 3.5–4 m in diameter and 0.8 m deep.[65]

Often we find simply an enclosed vaulted reservoir, and it is hard to tell whether purification was part of its intended function, since on going through a tank designed for any function – such as a junction with a branch line arriving or leaving – the current *would* slow down and impurities settle, whether that was the chief purpose intended or not. Rarely do we find an open settling chamber, as at the 'Grüne Pütz' at Cologne (Fig. 37), where the underground channel leading from the springs into the aqueduct conduit is interrupted by a rectangular tank, open to the sky and surrounded by a decorative coping, on much the same principle as the junction reservoir already noted as Eiserfey and possibly again serving as a local point from which to draw water.[66]

On the other hand, Frontinus does specify that the measuring equipment for recording the discharge, whatever it is, is often installed and operated in a *piscina*, a small reservoir and hence presumably a settling tank. Indeed, he specifically identifies one such as being ('ubi ... linum deponunt', *Aq*. I, 19), adding that this particular one is covered ('contectis piscinis'); he also adds that there is measuring equipment in it. In spite of this, I would be inclined to think that it would be so much easier and more satisfactory to manipulate the equipment in the open, where one could see what one was doing, than in the dark and awkward

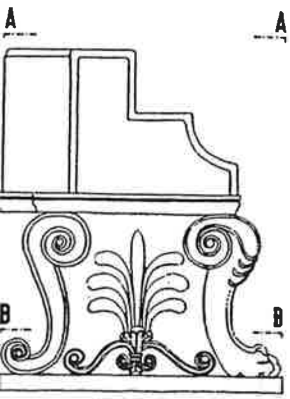


77. Rome: settling tank complex on the Aqua Virgo, near the Via Latina (J-P. Adam).

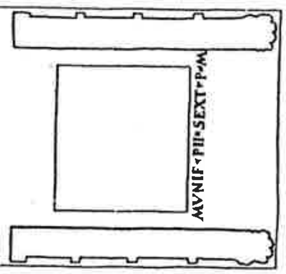
confines of a covered tank full of water, that the fact that the measuring equipment was often mounted at a settling tank[67] would indicate that many of them were uncovered. I must readily grant, though, that not many such have been found.

The normal form is a barrel – or cross-vaulted chamber or set of chambers – through which the water makes its way (Fig. 77). The importance of the settling may be gauged from the pebbles found in the settling tank of the Anio Novus (a notoriously impure stream) at the Villa Bertone, Capanelle, shortly before its entry into Rome. The pebbles are the size of a pea and completely round, having apparently made the journey all the way from Subiaco in the Sabine Hills along the bed of the Anio Novus, a distance of some 70 km. Even more impressive is the amount. Not only was the tank entirely full of them when discovered, but with them the modern owner of the property, a certain Cav. Bertone, 'has gravelled about a kilometre of avenues'. The mound upon which his villa stands also 'is artificial, and owes its origin to the refuse of the cleaning tank of the Anio Novus', from which was also forthcoming so much sand that 'Cav. Bertone was able to make plaster for six or seven buildings on his farm'.[68]

Nothing could speak louder for the vital role settling tanks played in the Roman aqueducts than this great heap of rubbish filtered out of the Anio Novus: for though not all streams were as impure as this, neither is there any way of telling how often the tank had already been cleared out and the pebbles carted away in antiquity before this enormous heap began accumulating in the period of neglect. We may also note that at its source the Anio Novus drew directly on the waters of the river Anio. This proved too muddy, and so Trajan realigned the intake to draw from the middle of three large pleasure lakes which Nero had created at Subiaco by damming the river, and which thus now acted as gigantic settling tanks for the aqueduct; the great mass of sand and pebbles that ended up at the Villa Bertone was thus only the final residue that escaped this screening process, from which we may with profit speculate on what would have been the result had there been none at all.



Elevation – side



Plan – B-B

pendently of them. One such as alongside the isesteads on Hadrian's

10
Urban Distribution

It is very likely that less than half the water that was taken into the aqueducts ever reached the city.

Herschel, p. 195

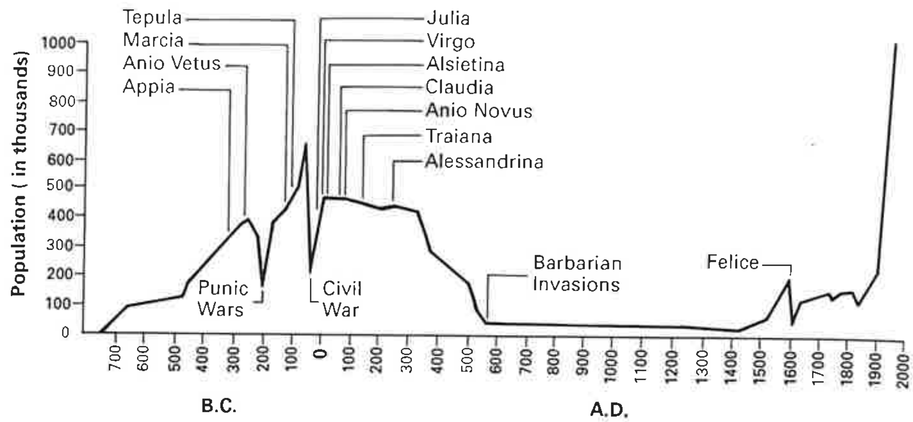
Filtration

On arrival at the city the water had already been largely filtered, both by small settling chambers cut in the floor of the channel itself and by large settling tanks and reservoirs built, as has been described, at intervals along the line of the aqueduct. By these means a good deal of the

Aqueduct	*Quinariae*	*m^3 per 24 hrs*
Appia	1,825	73,000
Anio Vetus	4,398	175,920
Marcia	4,690	187,600
Tepula	445	17,800
Julia	1,206	48,240
Virgo	2,504	100,160
Alsietina	392	15,680
Claudia	4,607	184,280
Anio Novus	4,738	189,520
TOTAL		992,200

188. Discharge of Roman aqueducts, calculated from the *quinaria* figures of Frontinus (Grimal).

sediment had already been removed, though not by any means all, if there was a lot of it to start with. We have already noted the vast heaps of pebbles removed from the Anio Novus by the settling tank at the Villa Bertone, Capanelle, but it is hard to know what conclusion to draw from it. One is tempted to think that the tank was plainly very effective, and how bad the water would have been on arrival at Rome if the tank had not been there. But we have Frontinus' word for it that in fact the Anio Novus



189. Graph relating dates of building Roman aqueducts to growth of population (Pace-Pediconi).

water *was* very bad and contaminated any other with which it was mixed. And all those pebbles that were screened out at the Villa Bertone, since they came from Subiaco, had already successfully run the gauntlet of all the other settling tanks en route, including the big *castellum* at Grotte Sconce. One would have thought that it, at least, would have been able to stop solid impurities like pebbles (as opposed to mud), and yet all those millions of pebbles at the Villa Bertone must have passed through it in order to get that far. One must therefore ask how many more million that we do not know about also got past the Villa Bertone, and were still in the water when it got to Rome? And, of course, at Rome three aqueducts, the Appia, the Virgo and the Alsietina, had no settling tanks at all and the water arrived unfiltered; the Alsietina, the worst of all, was perhaps so bad that it was adjudged useless even to try to clean it up.[1]

However, it was common for such a settling tank to be provided at the end of the aqueduct's run. All that was really needed was a large tank where the speed of the current would be sufficiently slowed in passing through for impurities in suspension to settle to the bottom, but we do find more elaborate arrangements. A common principle was to have two or more chambers so communicating that the water passed through all in turn, becoming progressively purer. With two chambers, it might be possible to close one and drain it for cleaning while the other continued in operation. Where the chambers were arranged at different levels, the water might be made to arrive first at low level and leave from above, to assist the settling process.[2] Otherwise, a typical example is that on the Virgo, where the water circulates through four chambers in turn (Fig. 77).[3] The lower has an opening low in one side running directly into the sewers, to facilitate cleaning. The floor of settling chambers was also

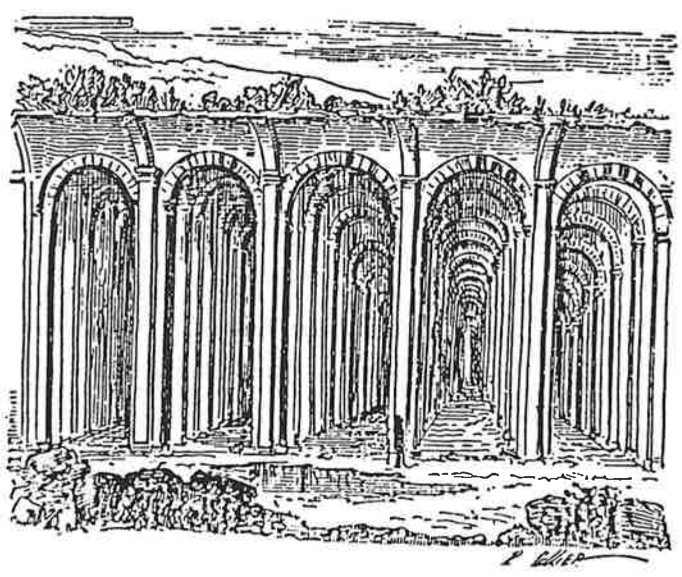
190. Ampurias: filter formed by a circle of amphorae, probably packed with charcoal and sand.

often tilted at a slight angle towards a drain, to facilitate shovelling out the accumulated debris,[4] access for the workmen being provided by a manhole in the roof which, as in most Roman construction, was normally vaulted. Properly speaking, in such installations the water was not filtered, but simply cleared by allowing impurities to settle by gravity. It could likewise be cleared by letting it flow across a bed of sand, or actually filtered by having it penetrate and physically pass through a barrier of some porous cleansing agent, but this was rarely done on aqueducts, where the volume of water to be treated and the speed with which it was passing through ruled out such efficient but leisurely methods.[5]

Nevertheless, it was done. At Ampurias (Fig. 190) we find a filtration plant where, apparently, the water percolated through a circle of amphorae packed with charcoal and sand, though this was in a cistern and treated only rainfall – Ampurias had no aqueduct.[6] More appositely, an actual filter across an aqueduct channel has been preserved at Cirta (Constantine) in Algeria. It was formed by a 60 cm thick wall of sandbags built at an angle across the channel, here 1.5 m wide. On the downstream side of this barrier were constructed a series of eight small channels, each 10 cm wide, separated by planks, and running side by side along the floor of the conduit. They could be followed for a length of 12 m, and bore traces of a fine white sand, which was apparently also what was inside the bags.[7] However, we must remember that this was on an Algerian aqueduct. In North Africa, where water was a rarer commodity than in

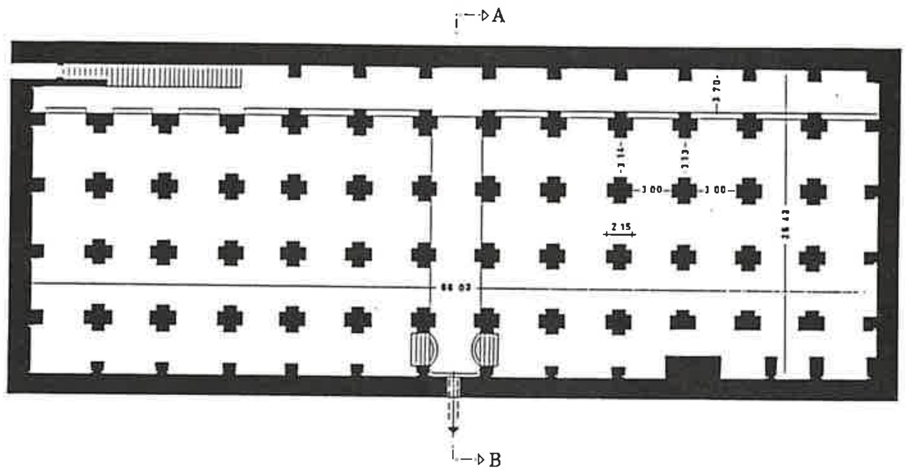
191. Baiae: the Piscina Mirabilis reservoir; capacity 12,600 m^3 (photo: K. Grewe, Bonn).

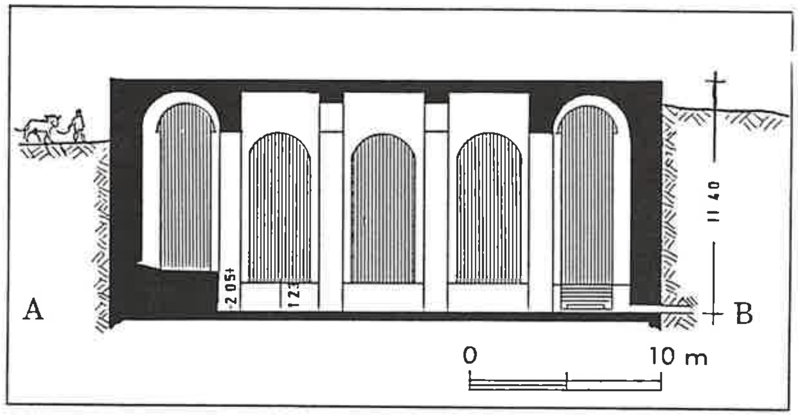
192. Cistern (reservoir) at Bacoli (Baiae), the 'Cento Camerelle' (Daremberg and Saglio).



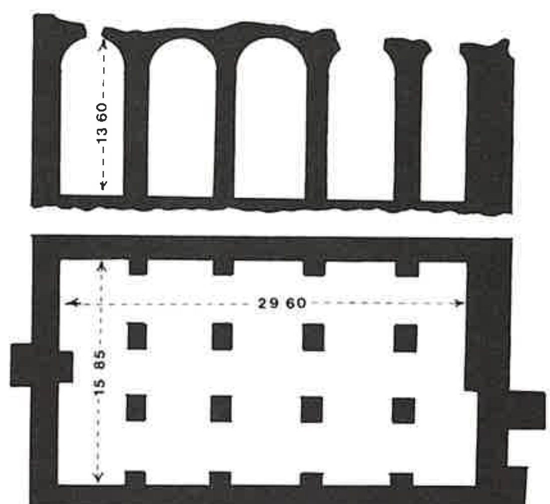
191. Baiae: the Piscina Mirabilis reservoir; capacity 12,600 m³ (photo: K. Grewe, Bonn).

192. Cistern (reservoir) at Bacoli (Baiae), the 'Cento Camerelle' (Daremberg and Saglio).

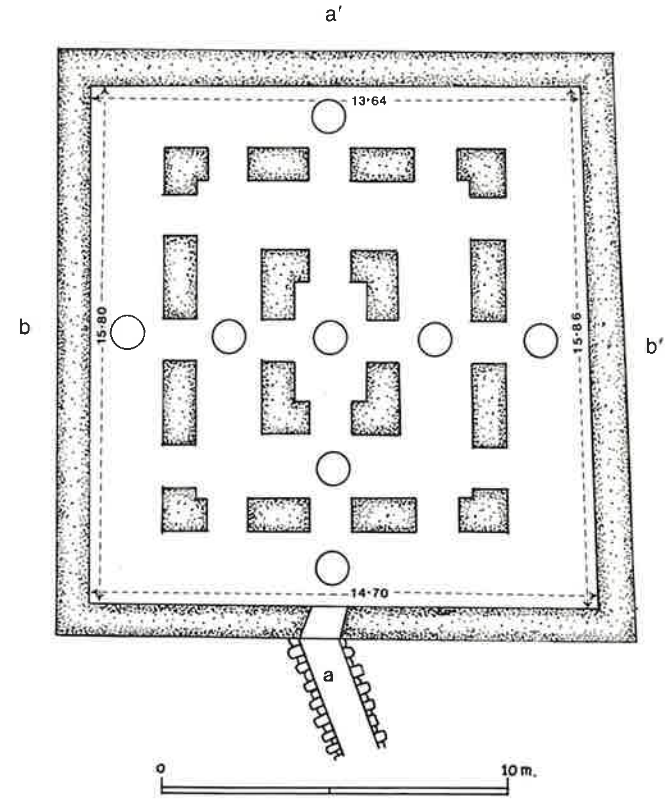




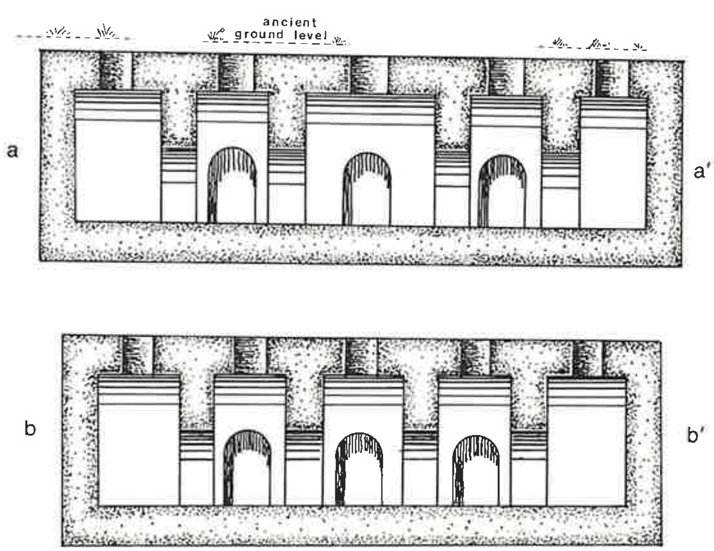
193. Cistern at Bacoli: (above) plan; and (below) section (J-P. Adam).

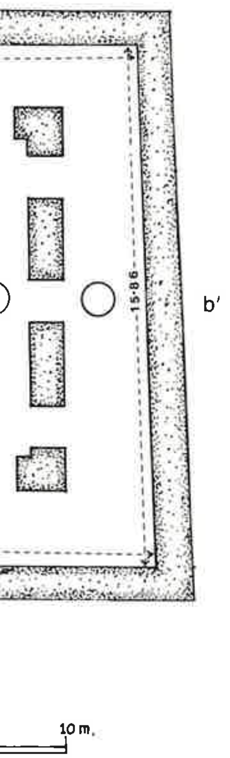


194. Saldae (Bougie, Algeria): cistern, almost 30 x 16 m (Birebent).



195. Lyon: cistern at the Grand-Séminaire, Fourvière ('La Grotte Berelle'): (above) plan; (below) longitudinal and transverse sections (de Montauzan, revised by J. Burdy and L. Jeancolas).





La Grotte Berelle'): (above) plan;
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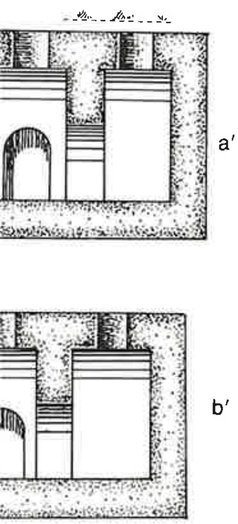

Europe, the Romans do not seem to have been able to afford the luxury of constant offtake as practised in Europe, and on arrival at the city the aqueduct usually discharged into great storage reservoirs, from which supplies were drawn as required. The Cirta filter is on a channel linking two such reservoirs, and presumably the water was fed through only as fast as the filter could deal with it, so that once again we are not dealing with a main aqueduct in full, continuous spate. We must therefore almost rule out filters as part of the normal fittings of an aqueduct. Grilles, on the other hand, were probably common. There is evidence for one on the outflow of the aqueduct into the *castellum divisorium* at Nîmes, and they have also been restored in the *castellum* at Pompeii. No doubt there were plenty of them, and it is perhaps surprising that more have not been actually found.[8]

The *castellum divisorium*

We now reach what is both one of the most complex and least studied aspects of Roman water supply, the urban distribution system. The first step depended on how much water was available. If supplies were limited, the aqueduct might at this point discharge into a large storage reservoir, to be used as needed. As noted, this was particularly common in North Africa, where it ranks almost as standard practice, but these large reservoirs are also found in such well-watered regions as Misenum (the one there, known as the *piscina mirabilis*, is 70 × 25.5 m, 15 m deep, and has a capacity of 12,600 m^3; it was fed by the Serino aqueduct and perhaps supplied the fresh-water needs of the fleet at the Misenum naval base), Baiae (the 'Cento Camerelle'; Figs, 191, 192, 193), Constantinople and Lyon (Fig. 195).[9] Such reservoirs were usually set low in the ground, or actually underground, and roofed over, usually by concrete vaulting. In plan they might look like what one could only call a kind of subterranean hypostyle hall, the roofing vaults supported by rows of columns, piers, or walls pierced with doors to allow the water to circulate. The floor, at Lyon at least, was slightly concave with a drain in the middle, to permit cleaning. In Tunisia an outstanding example is the Bordj Djedid cistern at Carthage, into which the Carthage aqueduct emptied after a run of no less than 90.43 km from its source. This great cistern, reckoned by Rakob the largest in the ancient world,[10] was oblong, 39 × 154.6 m, the size of an entire city block, and subdivided into eighteen transverse compartments. Its capacity was 25,000–30,000 m^3, but to put this into context we should note that this represents about a day and a half's discharge for the aqueduct.[11] For all the size of the cistern, therefore, it only contained something over a day's supply, and we must not consider it as anything like the storage reservoirs in modern work (e.g. at the Marathon dam in Greece) which effectively store enough water for months. On the other hand, it was no mere *castellum divisorium* but a major source of supply.

Unless it was purely for emergencies, I can imagine only two ways of using it. Either it was a reserve for use when the aqueduct ran low, by adding in a little from the cistern every day to supplement supplies until the aqueduct discharge picked up again; or daily consumption did, in fact, exceed what the aqueduct could bring in, at least in the hours of daylight, so that the reservoir was in effect topped up every night to meet the next day's demands.[12]

If this second were true, it would of course imply a whole philosophy of water supply radically different from the continuous offtake principle traditional to Roman aqueducts. It would imply the acceptance of storage against future needs and something akin to the recognition of peak and off-peak hours: an un-Roman philosophy, but they might have been driven to it by actual lack of water. Certainly the widespread use of cisterns and reservoirs, some even aqueduct fed, in minor and rural sites, must have accustomed the North Africans to the idea of drawing upon a store as required, and filling it up as opportunity offered. Is it not then possible that they took the mental leap necessary to extend this principle also to major aqueduct supplies?

Setting aside such storage cisterns, we come to the *castellum divisorium* proper (Fig. 199). As normally understood, this is a small tank (at least compared with the cisterns) located usually at the edge of the city. The aqueduct enters it as one single unit, and leaves it as a number of separate branches, sometimes running direct to their point of use, if it is one, such as baths, using enough water to justify a pipeline of its own, otherwise running to a number of sub-*castella* or water towers, where the branches are further subdivided into individual lines serving fountains and private houses. The *castellum divisorium* thus is in effect a junction box, marking the end of the aqueduct proper and the start of the urban distribution process; it is sometimes referred to as the terminal *castellum*. It is normally to be found on the edge of the city, perhaps on or just inside the walls, and, in order to give service as widely as possible, at the highest point the incoming aqueduct can reach given the level of its arrival. At Pompeii it is at the Porta Vesuvii; at Nîmes on the higher ground at the north end of the city; at Fréjus it abutted on the city walls at the Plateau du Moulin-à-vent – the aqueduct serving it ran along the top of the walls; at Arles it was facing the amphitheatre; at Rome the various terminal *castella* are in different locations, but most fairly high.[13] Modern expositions are sometimes confused, and are based largely on three *castella* – Nîmes, Pompeii, and the ideal *castellum* described by Vitruvius. This last has exerted great influence, for none of the existing *castella* correspond to Vitruvius' prescription, and a great deal of confusion has been caused by efforts to make them do so.[14]

Vitruvius' prescription for a *castellum* is almost better understood by a written description alone, without the illustrations and diagrams that normally accompany it in any standard commentary, for these cannot but create clarity and certainty where Vitruvius may be unclear and ambiguous. To that extent, they may misrepresent the issue. What Vitruvius says is that a triple basin for receiving the discharge from the aqueduct should be attached to the *castellum*; and three equal pipes should bring water from the *castellum* to the three compartments of the basin, so arranged that when the two outside compartments overflow, it goes into the middle one. From the middle one, pipes go off to serve the public drinking fountains: the other two serve the baths and private homes. This is to prevent private users from cutting into the public supply.[15] If the reader finds this account not entirely straightforward or readily understandable, it is because I have tried to reproduce what is actually in Vitruvius. Some points are plain. There is to be a tank divided into three, and each division is to serve one of the three main categories of customer: public fountains, baths and private houses. Priorities are established, and the overflow is the automatic device set up to maintain them.

Other points are not so clear. If the three basins are served by pipes of the same size, will they not get the same amount of water? How will they then ever overflow into each other? The answer is apparently to set the middle one, the recipient of the excess, lower than the other two, so that the overflow goes only in one direction; what happens to its own overflow is not stated. Again, surely the three equal pipes from the *castellum* to the basins must be bigger than the offtake pipelines from the basins to the town, or at least bigger than the two outer ones, otherwise the pipeline could carry everything the *castellum* pipe delivered and there would again be no overflow, except perhaps from the *castellum* itself. Commentators even differ on whether the aim of the arrangement was to protect the private users or the public.[16] It may have been both. The tripartite division of available supplies (by 'three equal pipes' – *tres fistulae aequaliter divisae*) guarantees that both private and public customers have a given, and equal, volume of water reserved for them. It does not, as Callebat implies, recognise the priority of public fountains, in that it makes no effort to ensure that they are served first, and in time of shortage all three – baths, street fountains and private users – will go short alike and in equal proportion. There is no question, as has sometimes been suggested, of ensuring that the public fountains are the last to run dry. Such a course would be logical, but it is not what Vitruvius says. The overflow mechanism comes *after* the division into three, and in time of shortage will not operate because there will be no overflow. What it does ensure is that in times of abundance the surplus, once the commitment to private users and baths has been met, is not divided up but all goes to the fountains, which in this sense do have a priority. The private users have thus not a guaranteed minimum entitlement but an automatically enforced maximum. One may ask why, then, was there not simply a single overflow from the main *castellum*, leading directly into the public service line, without any three basins? This would cut out a lot of complications and produce exactly the same effect. The only answer I can think of is that the plan prescribed by Vitruvius is his own recommendation and purely hypothetical; no *castellum* actually conforming to it has ever been found. Vitruvius, after all, was not writing an encylopaedia of existing Roman building practice (though that is exactly what modern readers often take him for), but rather, based on that practice, a set of guidelines and recommendations: he tells us not so much how things were done as how he thinks they ought to have been done. And sometimes he is wrong.[17]

From Augustan times onwards, Pompeii had a single aqueduct. It drew its water from springs at Serino, near Avellino, whence it ran via Sarno and around the north side of Vesuvius to serve Naples and, eventually, the two big cisterns of Cento Camerelle (Baiae) and the Piscina Mirabilis (Misenum). From Sarno a branch ran to Pompeii, terminating in the *castellum* at Porta Vesuvii.[18] The supply channel was not very big – 30 × 25 cm (Fig. 49(b); ch. 5 n. 7 above), but the distribution arrangements were of remarkable – even needless – complexity. The entire *castellum* was housed inside a large brick building, and consisted basically of a shallow circular basin (Figs 196, 197).[19] After passing through two transverse mesh screens to remove the worst impurities, the water was faced with a row of three parallel exit channels, the entrance to each barred by a low wooden gate; the gates themselves are gone, but their bronze fastenings are extant. The water entered the channel, and so escaped through its exit, at the far end, by spilling over the top of the gate, which thus acted as a weir. From the exit the water ran into an ordinary pipeline of lead pipes, the central one (serving the fountains) being of 30 cm external diameter, and the two side ones 25 cm. The three gates were of different heights, so that the highest gate, which was on the channel serving private houses, cut off their supplies until and unless the water level in the main body of the *castellum* rose high enough to spill over it and start flowing down the channel; conversely, the lowest gate (that in the middle) governed access to the public fountains, which, if the water level sank, were thus the last to dry up. As Eschebach says, the principle plainly reflects the system of Vitruvius, but it is not the same. By introducing the selection mechanism before the water is divided up between the three channels, instead of after, its operation is radically changed. The private users have no minimum entitlement, for until the needs of the other two groups have been fully satisfied, they get none at all. Nor is Vitruvius' scheme simply reversed, for in the event of a large surplus it does not automatically now all go the private users, just as Vitruvius directed it all to the public fountains. When the water is high enough to spill over into the private users' channel, it still continues spilling over even more into the other two, so that the surplus is itself then divided among the three. Thus the Pompeii *castellum* genuinely

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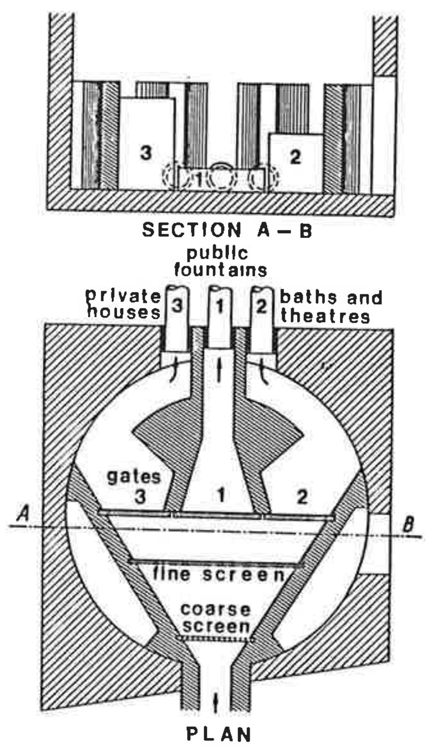
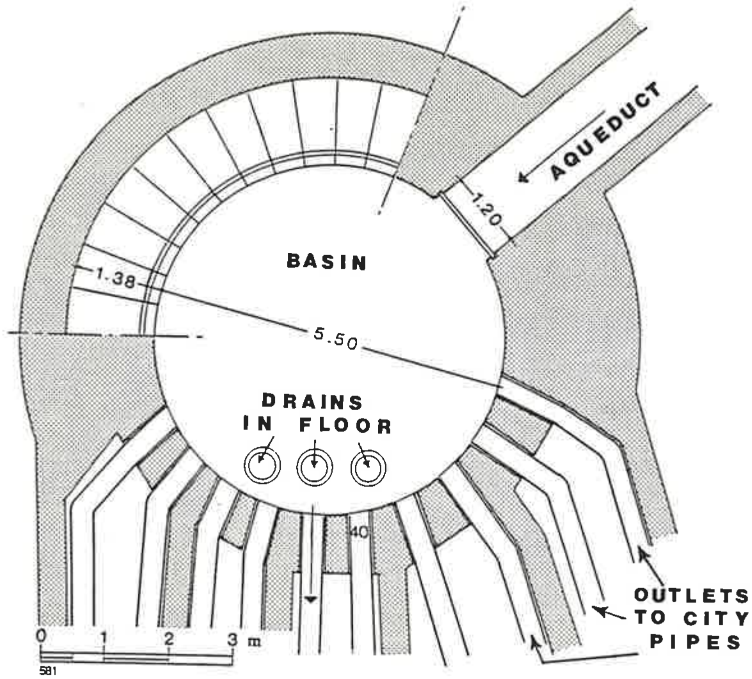
196. Pompeii: *castellum divisorium*, at the Porta Vesuvii. Plan of the interior arrangements, Fig. 197. Water mains serving the city came from the three large openings at the base of the wall.



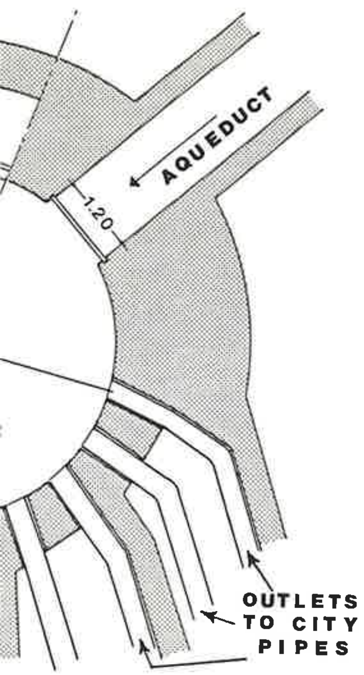
197. Pompeii: plan of distribution arrangements inside *castellum divisorium* at Porta Vesuvii: plan and elevation (Kretzschmer).



198. Nîmes: *castellum divisorium*, plan (J-P. Adam).

does fulfil the principle enunciated by Callebat, and gives not just a preference but absolute priority to public drinking water: until this need was filled, and in full, all other pipes remained completely empty. Of course, one must not forget that, as in other cities, piped supplies were extensively supplemented by wells and cisterns, so that this restriction was perhaps not as onerous a burden as might be imagined.[20] The real surprise perhaps is twofold. Is not this a very complex arrangement for a very small aqueduct – the conduit is 30 × 25 cm and carries only half the discharge of the industrial leet at Dolaucothi? And could the same effect not have been realised just by building an ordinary tank and setting the three offtake pipes into its side at different levels? Of course, the wooden gates could easily be replaced by others of different heights, thus varying the proportion of water delivered to the three main pipes, and could even be lifted out altogether to permit unrestricted flow, so that the Pompeii system does have more flexibility than three pipes in the side of a tank.

The *castellum divisorium* at Nîmes (Figs 198, 199, 200) is certainly the best-known extant example.[21] Though today somewhat austere, not to say deserted, in aspect, it was in Roman times a place of popular resort. Its heart is an open, shallow, circular basin, diameter 5.5 m and 1 m deep.[22] In antiquity this was surrounded by a metal balustrade, over which visitors could lean and admire the swirling waters. Around it was



rium, plan (J-P. Adam).

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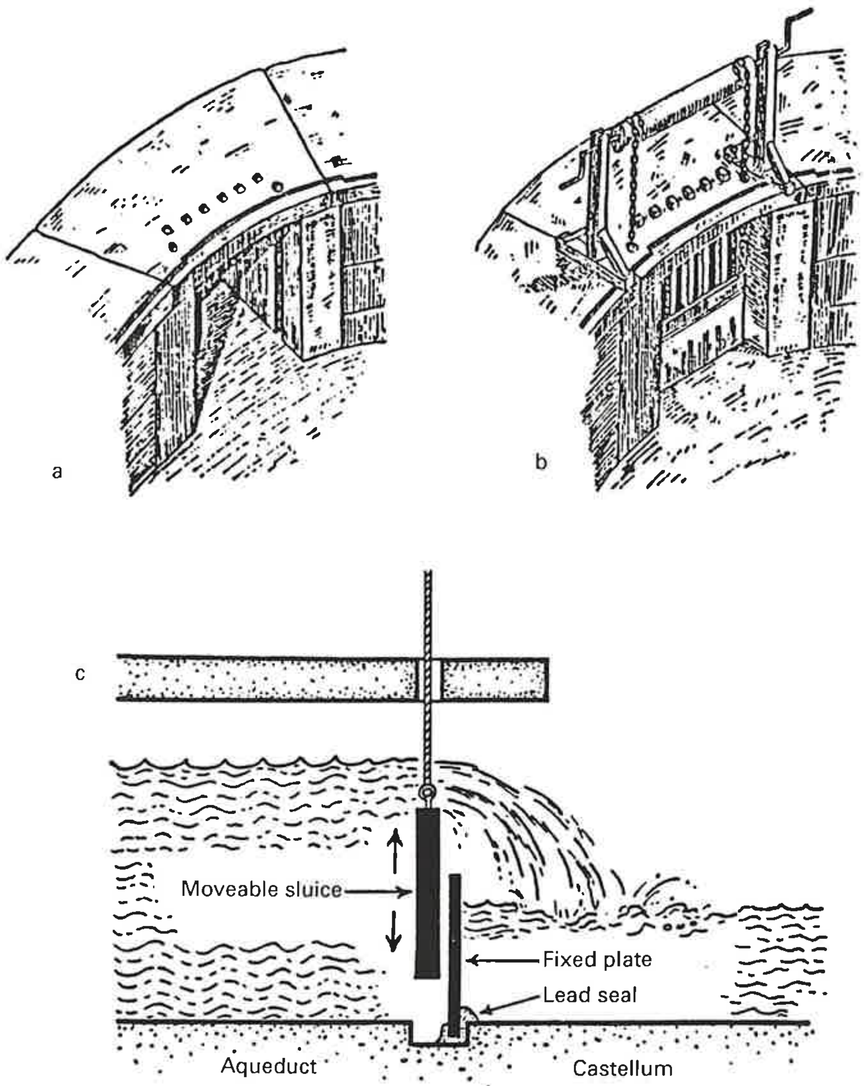
today somewhat austere, not to
times a place of popular resort.
basin, diameter 5.5 m and 1 m
ed by a metal balustrade, over
e swirling waters. Around it was

199. Nîmes: *castellum divisorium*. The water entered (from the aqueduct) through the large square opening (left), and left by a series of ten large lead pipes through holes in the sidewall; a further three ran from openings in the floor. For plan, see Fig. 198.

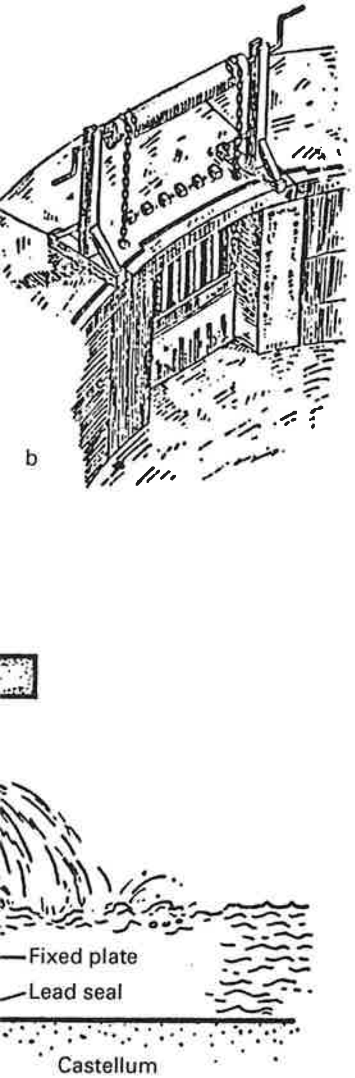
built some sort of enclosure with a tiled roof, Corinthian columns and entablature, and a wall decorated with a brightly painted fresco of fish and dolphins, an appropriately aquatic theme.[23] All of these were in a fragmentary state on discovery and have long since disappeared, so one cannot reconstruct the appearance of the edifice, but we would surely not be far wrong in visualising some kind of small but ornate pavilion, rather like that which a later age erected for the eighteenth-century *château d'eau* at the end of the aqueduct in the Promenade de Peyrou at Montpellier (Fig. 1). As at Montpellier, so also at Roman Nîmes was the water supply considered an object of civic pride well worthy of architectural celebration.[24]

The aqueduct entered this basin through an oblong opening to the east, to the left of the entrance doorway of the pavilion. This opening, 1.20 m wide by 1.10 m high,[25] was covered by a (stone?) grille behind which was a sluicegate controlling flow from the aqueduct into the *castellum*, apparently operated by a windlass mounted on the stone paving surrounding the basin, the connecting cables passing through two holes in the stone (Fig. 200). The sluice itself raises great problems. First, why is it there at all? It is natural to see it simply as an isolating sluice to shut off supply to the *castellum*, but when one remembers that it is supplied by a downhill, gravity-fed open aqueduct channel, one realises that the place to cut off the supply is somewhere a lot further back, where the water can



200. Nîmes: *castellum divisorium*, restoration of sluice (a) and (b) at entry point of aqueduct (Stübinger); (c) reconstruction of its possible use in measuring aqueduct discharge (A.T.H.).

be diverted into another channel: cut it off at the bottom of the slope and the result is an overflow and flooding. Second, because the sluice is tucked in underneath the stone cover slab of the paving, it cannot be lifted up to let the water flow, for there is no slot in the stone-work to let it through as it rises. It was perhaps in answer to this difficulty that the sluice was apparently made in two halves (Fig. 200 (c)). The lower half was a fixed lead plate, set permanently in position and sealed round the edges with



(a) and (b) at entry point of aqueduct
suring aqueduct discharge (A.T.H.).

t the bottom of the slope and
, because the sluice is tucked
ving, it cannot be lifted up to
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ifficulty that the sluice was
. The lower half was a fixed
sealed round the edges with

lead. Behind this slid the sluicegate proper. When it was raised, it and the lead plate between them closed the entire aperture, though it must have been a very leaky arrangement. When it was lowered, to rest behind the lead plate, the upper half of the aperture was opened and the water, provided it was deep enough, could flow into the *castellum*, pouring over the top of the sluice and plate as if it were a weir.[26] The reason for this complicated arrangement remains obscure, and could all have been avoided just by fitting an ordinary sluice in some position where it could be operated, either in the *castellum* itself, across the mouth of the opening, or, if it was desired to keep it tucked away inside the opening for the sake of neatness, then all that was required was a slot cut in the stone cover to let the gate rise clear of the water stream. The effect of the fixed plate would be to maintain a certain minimum depth and slow rate of flow in the aqueduct behind it, reducing wear and tear on the walls, but this would seem to be a minor factor.[27]

In the middle of the *castellum* are still to be seen one or two blocks of stone set into the floor (there are four marked in the *Archives* plan, n. 21 above), themselves carrying sockets for the mounting of some kind of barrier constructed across the *castellum* and through which the water flowed on its way from the entry sluice to the offtake pipes at the other side. This barrier, from the position of the blocks, seems to have been crescent-shaped with the convex side towards the offtake pipes, but apart from that we can only conjecture what it was like or what it did. There are two possibilities. One is that it was simply to create a disturbance in the water and aerate it from the eddies and turbulence thus caused – as the *Archives* publication puts it, 'pour lui donner une agitation qui, dans les idées des Romains, contribuait à sa salubrité … En arrivant dans le bassin par l'aqueduc, l'eau venait se briser contre cette barrière, tourbillonait, et se mélangeait d'air; elle était pour ainsi dire *battue* au moyen de cet appareil.'[28] The other possibility is that it was an arrangement like the gates in the *castellum* at Pompeii, and controlled the supply of water to the various pipes. Certainly such a provision was needed, for their openings show no signs of being fitted with sluices, and the pipes themselves, at a 40 cm external diameter, were too big for taps.[29] But for it to work, a separate sluice would have to be provided for each pipe, or group of pipes, and if this were installed in the barrier, then there would have to be a channel from sluice to pipe, to stop the water thus admitted also going into the wrong pipes. One thus postulates a metal barrier with a series of sluices, and behind it a row of parallel channels separated by dividers, such as planks set on edge, to connect the sluices with the respective pipe openings. This is not too different from what we have actually seen at Pompeii, though there were only three channels and the whole operation was on a much smaller scale, but, in the absence of any evidence at all, this is probably as far as guesswork can profitably be pushed.

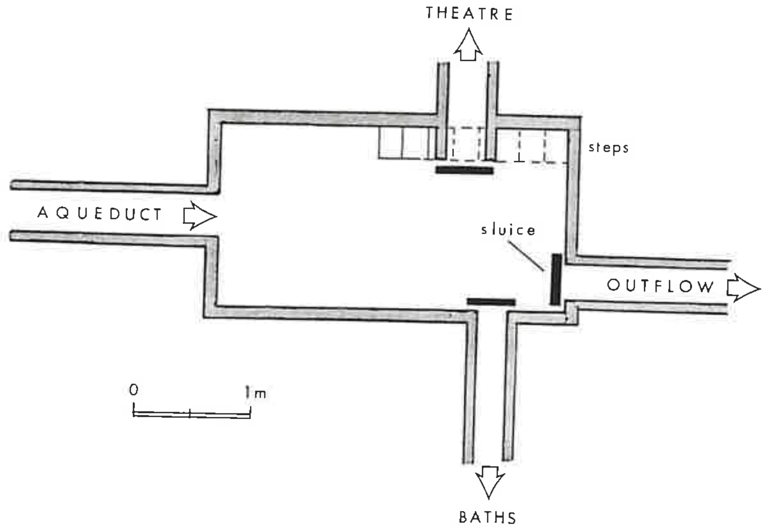
In the wall facing the entry of the aqueduct is pierced a row of ten large holes, which provided the offtake for the main pipelines serving the city. The row formed an arc, and the aqueduct was directly facing one end of it and at a right angle to the other: it was therefore not centred or aligned upon it, for whatever reason.[30] The holes are 56 cm above the floor and of 40 cm diameter. They have no ridge, flange, or recess of any kind for fixing into the hole the lead pipe that it carried, so that this must have been held in place by a ring of cement or plaster. No trace of this survives. The pipes themselves are also gone, though part of the calcium carbonate deposit from inside one has been found, giving the pipe's dimensions.[31] As with many other similar reservoirs, a problem is posed by the apparent absence of any sluices, taps or other control equipment on the pipes leading out of it; the same problem arises with the header and receiving tanks of the Lyon siphons. Setting aside the possibility of individual sluices on the metal barrier as too conjectural (though perhaps correct), how then was water shut off in one of these pipes? The normal answer is that there must have been a tap or stopcock on the pipe itself, now disappeared, but no taps of this size have anywhere been found. The stonework around the holes is completely flat and virgin, with no signs of fittings for sluices or anything else. There is only one other way that the supply could have been cut off without leaving a trace, and this is by lowering into the water a sheet of canvas to cover the hole, against which it would be held firm by water pressure. There is evidence for the use of this system from a later period – in Turkish hydraulics, which also used *castella*, it was one of the standard ways of turning off the supply. I do not, however, offer it here as anything more than an interesting possibility.[32]

Although in the *castellum* the ten holes are equidistant, once the pipes left it they were grouped into five pairs, each pair running in a hollow between two masonry side walls that divided it from its neighbours and also presumably supported the stone slabs of the pavement above. None of these pipes have been traced any further, and we do not know whether they simply represent a geographical division (mains branching off to five different parts of the town) or a division by category of customer, like the threefold division of Vitruvius – private, public and baths. If so, a different political or social principle seems to have been involved, since all ten offtake holes are at the same level and all users, of different kinds, are treated on a basis of equality, as opposed to the efforts of Vitruvius and the Pompeii authorities to establish priorities. Of course, if there were control sluices somewhere they could have been used to regulate distribution; this remains conjectural.

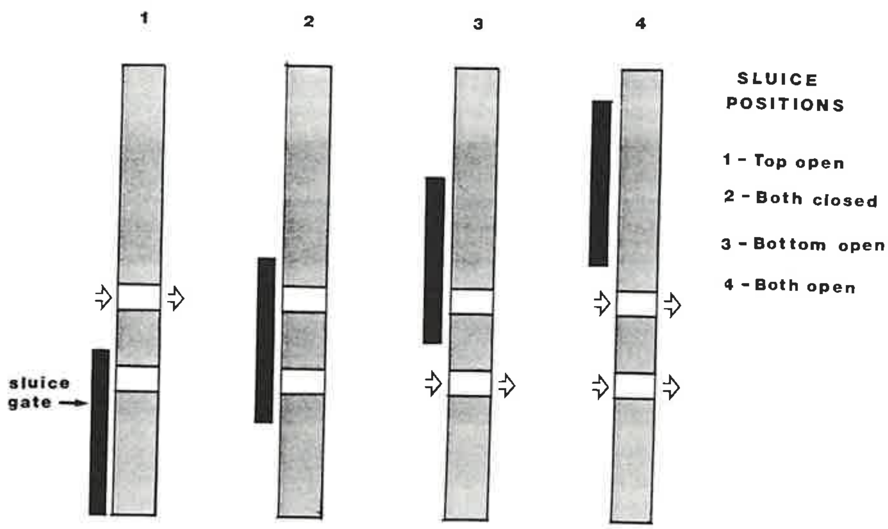
Finally we may note that in the floor of the *castellum* immediately in front of the bank of ten orifices in the wall, is a further set of three. These, unlike the others, have a recessed ring around the edge of the hole to provide a seating for a lid to close off the hole. Moreover, projecting from the edge of the ring into the stonework are three short, recessed slots, evidently to engage with three projecting lugs on the circumference of the lid; presumably they prevented the lid from turning in its seating, though why this should be thought either necessary or advisable I do not know. There is no sign that they could be used in any way to lock the lid down and in place, and presumably it was held there by gravity and the weight of the water above. Presumably that would be enough to hold down even a wooden lid and prevent it floating, but the lid may have been of stone in any case.[33] Presumably also there was some method of unplugging these holes from above when the castellum was full; a rope or chain attached to each lid would be enough. As for purpose, the existence of these holes has sometimes led to misapprehensions, evoking memories of Vitruvius and his two-level overflow system of priorities. On this basis, the three holes in the floor would serve the top priority since, being lowest, they would be the last to run dry: Ashby fell into this trap and asserted that here 'three main pipes catch the maximum flow and ten others draw equally from a higher level in the tank'.[34] But in fact the three holes go straight into a drain. Why, then, are they there? A single orifice would be more than adequate for draining the *castellum*; with the inflow shut off, somewhere, it would be empty in two or three minutes. The use of three implies that either the *castellum* had to be cleared as fast as lightning (which makes no sense) or, if the inflow was *not* closed off, a large volume of water was, on occasion required, and quickly, down this drain. The most likely explanation here is that long ago urged by Auguste Pelet, that it was for a *naumachia*, at the theatre nearby.[35]

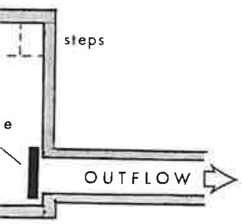
These three terminal *castella*, two real and one hypothetical, are the evidence upon which nearly all our discussions of the topic are based. Other examples actually excavated and known are very few. One may cite the small but remarkable *castellum* from Thuburbo Minus (Tebourba) in Tunisia published by de Montauzan[36] (Fig. 201). An oblong chamber, some 1.5 × 2.8 m and 1.5 m deep, was entered by the aqueduct at one end. From the far end and the two sides three lead pipes served, by de Montauzan's account, the baths, the theatre(?) and the cisterns. This is a North African context, where scarcity of water means it has to be used as required from storage cisterns instead of kept running all the time as in the fountains of Rome, but given this substitution what we have here is basically the Vitruvian tripartite division (reflected also at Pompeii). In view of its small size, this is plainly not conceived as a storage reservoir – that is what the cisterns are for. It is a junction box, a convenient way of splitting the main channel into three, with control sluices on each (the vertical grooves for which are preserved in the stonework). It is one of these sluices that is the most noteworthy feature of the tank, for it controls two apertures simultaneously (Fig. 201 (below)) and can be set in four positions, making it a device of remarkably sophisticated flexibility.[37]

From the *castellum*[38] the aqueduct is divided up into branches. These



201. Tebourba, Tunisia: (above) *castellum divisorium*, serving theatre and baths. The main outflow to the cisterns which serve the city is controlled by a sluice (as marked) with four possible settings: (below) four-position settings of this sluice.





ng theatre and baths. The main
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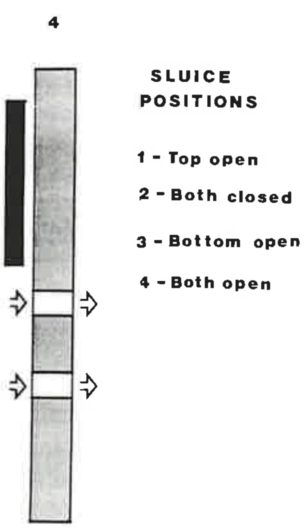
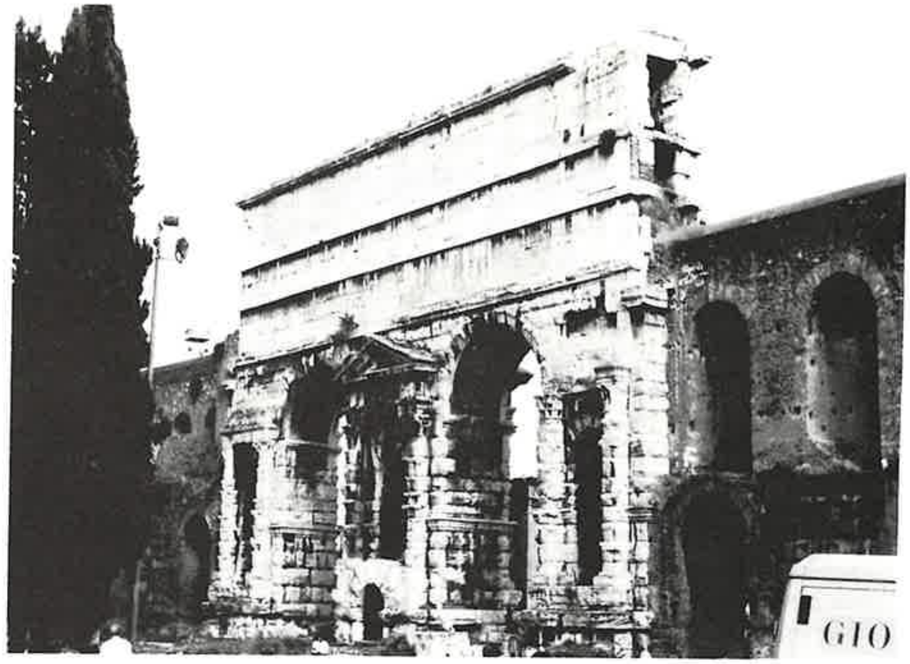


may be either branches to the three different categories of user, as apparently at Pompeii and Thuburbo, or, as at Nîmes and Rome, to different regions of the city, the division by category to be made later, if at all. These branches might be lead pipes, in which case the *castellum* marks the point where the water leaves the open channel of the aqueduct to enter the environment of enclosed low-pressure piping in which it will be carried henceforward, as at Nîmes and in our Fig. 198. Alternatively, the branches, particularly if the aqueduct is so big that to carry the water you would have needed a whole battery of pipes, as in siphons, could be conventional open channels, like the aqueduct itself. Many of the aqueducts of Rome divided up into branches in this way serving different regions of the city (some, like the Rivus Herculaneus of the Marcia, having their own names), their channels running on arcades or subterraneously as terrain and levels might require. Thus ceremonial arches sometimes carry an aqueduct on top as part of the construction, to get it across the street,[39] and the same is true of city gates if the aqueduct is carried on top of the city walls. The best known example of this is the Porta Maggiore (Fig. 202), where the Claudia and Anio Novus are clearly visible on top of the city walls and crossing the Viae Praenestina and Labicana.[40] The city walls did sometimes provide a convenient substitute for an arcade in carrying the aqueduct round from one part of the city to another, but there was a potential snag: built to military, not hydraulic, criteria, and usually in existence before the aqueduct came, they were liable not to be level enough for an open water channel. This might sometimes be corrected by building the walls higher where necessary, but there were limits to how far they could be modified. At the north corner of Fréjus the city wall, here making a right-angle bend, also rises at the apex of the angle to a height hydraulically unacceptable. The water-channel, therefore, which is here running on top of the wall, leaves it to cut across at an angle following the lower ground and pick up the wall again when it has made its return and has descended again to a suitable level.[41]

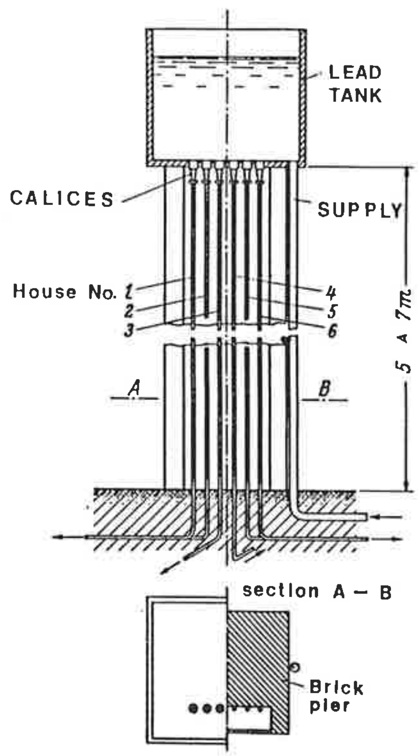
The secondary *castellum*

As the water thus continued its course, whether by pipe or conventional aqueduct, it next reached a smaller, secondary *castellum*; sometimes this was raised on top of a brick pier to become a water tower (Figs 203, 204). It was from these that pipes then branched off to supply individual customers, and they were quite numerous. Rome had a total of 247 such *castella* (Fig. 205).[42] Despite this, not many of them have been found outside Pompeii: at Rome discoveries are rare, and 'nous ne connaissons en Gaule que bien peu de ces châteaux d'eau: deux ou trois à Lyon et de façon assez incomplète.'[43]

It is also probably again a mistake to seek to reconstruct a uniform



202. Rome: Porta Maggiore, the point at which all eastern aqueducts entered Rome together. The channels of the Aqua Claudia and (above) the Anio Novus are clearly to be seen running on top of the walls.



203. Pompeii: water tower, or secondary *castellum* (Kretzschmer).

Porta Maggiore, the point at
stern aqueducts entered Rome
e channels of the Aqua Claudia
the Anio Novus are clearly to be
on top of the walls.

: water tower, or secondary
etzschmer).

204. Pompeii: water tower. Clearly visible are the vertical recess carrying the piping up its side to the tank on top, and the public fountain (the square stone basin) at its base.

205. Table showing allocation of the *castella* in Rome among the various aqueducts, in the time of Frontinus (Pace).

Appia	20
Anio Vetus	35
Marcia	51
Tepula	14
Julia	17
Virgo	18
Alsietina	—
Claudia and Anio Novus	92
TOTAL	247

system, consistently employed throughout the Roman empire. They were probably of different shapes, round or rectangular. As well as subdividing the supply among other customers they probably also served each other, for there are far too many of them, at least in Rome, to have all drawn their water directly from the terminal *castella*. A lot of them must have been arranged in series, the water passing through several *castella* in turn with some of it being diverted at each one into the pipes of the users. Again, Frontinus often speaks of water being switched from one aqueduct to another, and throughout the city the public fountains were in general equipped each with two water jets drawing upon different aqueducts, as a stand-by in case service was interrupted. This does seem to indicate a whole network of interconnections and switching facilities that we can only guess at, but which must have been of cardinal importance in day-to-day operation. The role of the secondary *castellum* represents perhaps the greatest lacuna in our understanding of Roman urban distribution.[44]

Frontinus raises yet another point, by quoting a law of 11 BC forbidding private users to take their supply line directly from the aqueduct conduit: it had to be taken from a *castellum*.[45] Two implications are plain. Previously many private users did tap the conduit directly for their supply lines, and the making of the connection was not done by the waterworks staff, and was outside their jurisdiction. Of course, such connections were often made illegally, either by the users themselves or by the waterman for a bribe, but that is not what we are dealing with here. If it were, the illegality of taking the water would itself be enough for a prosecution; and if the waterworks staff had a monopoly of installing the connections, all that would be required would be a directive from the *curator aquarum* telling them not to put the *calix* into a conduit but to go to a *castellum*. Instead, it took a decree of the senate, acting on a report of the two consuls, to put a stop to the practice. We may therefore reasonably assume that at this time private users who had the right to a water service also had the right to make their own arrangements for putting in the connection, without employing the official watermen.[46] We thus have a suggestion that this public service had perhaps been to some extent 'privatised', and the private contractors had adopted the practice of saving money by taking the lead from the nearest stretch of conduit handy instead of carrying the line to a *castellum*, thus cutting out the secondary *castellum* from the system. They evidently had to be stopped, because the main pipes and conduits were suffering ('being ripped apart', Frontinus says) from the great number of small-gauge offtakes being inserted into them, often none too carefully. Henceforth, all leads had to come from a *castellum* where they could be properly supervised both in installation and in operation.[47] On the other hand, when enough private users were involved to justify it, they could club together and build a private secondary *castellum* at their own expense and for their own use, at a location approved by a waterworks inspector; this could be supplied by a mains pipe from the nearest public *castellum*, and the local proprietors could then individually take their supplies from it. On this basis, there was in Rome a further subdivision in secondary *castella*, into private and public. There was presumably no difference in design or function, except in so far as while the public *castella* would, or at least could, supply public fountains as well as private houses, private *castella* were exclusively for private use. Presumably also, being privately built, cleaning and maintenance were a private responsibility and not borne by the water office, but we really have no way of knowing. We do not even know how many of them there were in Rome.[48]

At the point where it left the secondary *castellum*, each one of the lead

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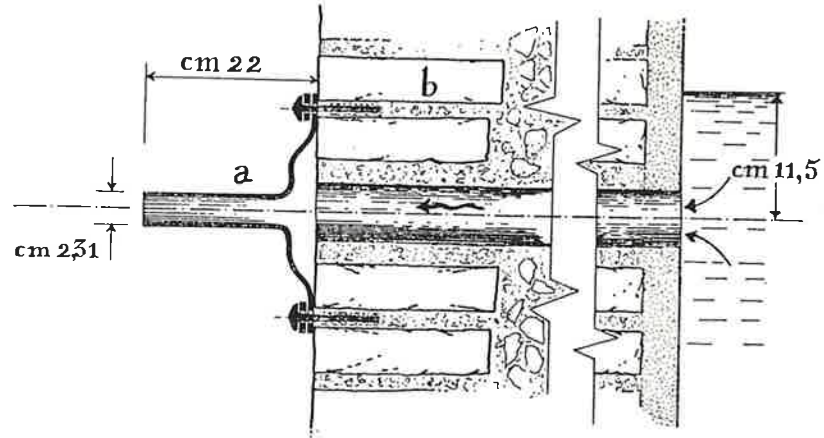
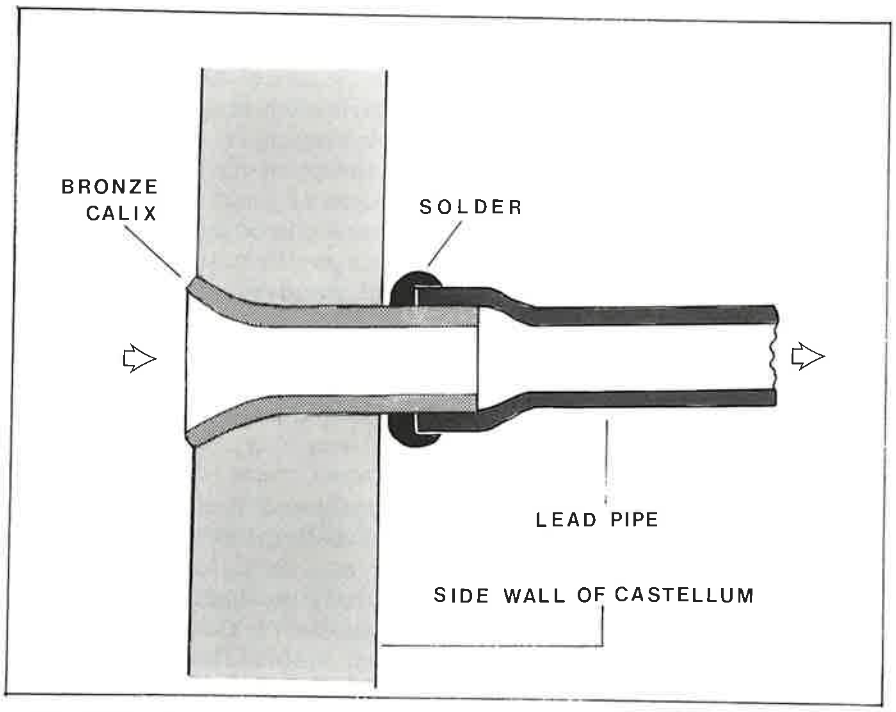


206. *Calix*, *quinaria*-gauge, mounted on a *castellum*; in this reconstruction the *calix* (a) is attached to the outside face of the *castellum* wall (b). The distance below water level (11.5 cm) is in accordance with the calculations of Di Fenizio (Pace).



207. *Calix* embedded in the *castellum* wall, with lead pipe attached (right) (Forbes).

pipes into which the water now passed was fitted with a *calix*. The *calix*, sometimes called an adjutage, was a bronze nozzle or tube (Figs 206, 207) at least 12 digits (21.6 cm) long, and of standardised size. It was mounted in the side wall of the *castellum*, so that it received water from the tank, and passed it on to the lead pipe which was fixed to the other end.[49] The *calix* thus governed the amount of water the user could receive, and, in the absence of water meters, was the device whereby his entitlement was officially regulated and enforced. It was based upon, and automatically delivered, the maximum discharge attainable by continuous running, day and night. No one looked askance at that, since the whole Roman aqueduct system operated on the same principle, and no doubt the proprietor, who had paid for his grant of water rights, regarded water flowing continuously night and day not as waste, but as something he paid good money for, and was *entitled* to. At the same time, the unscrupulous were not above wreaking an improvement by taking a crowbar to the *calix* and enlarging its orifice; this is why the calix had to be made of bronze, harder to deform than lead.[50] It was also specified that at least the first fifty feet of lead pipe following the *calix* had to be of the same size as it was. Apparently it was feared that if a large pipe was fitted leaving the *calix* as a short bottleneck only a few inches long, it might act hydraulically as a sort of funnel in reverse and unduly increase flow through the *calix* by the suction so created.[51]

The *calices* came in regular sizes to match the size of the standard pipes in use,[52] and, since they controlled the distribution and consumption of the water, were the key to the aquatic book-keeping on which the whole system was founded, particularly from the viewpoint of a bureaucrat such as Frontinus. The calculations involved were of great (one sometimes feels, needless) complexity, and offer perhaps one of the best examples extant of the cumbersome nature of Roman mathematics.[53] It was not helped by the fact that two quite different standards of measurement, inches and digits, were involved, the digit being 1.8 cm and a measurement commonly used in Campania and a large part of Italy, while the inch was 2.4 cm and of Apulian origin. The waterworks staff had at their disposal a repertoire of no less than twenty-five *calices*, though only fifteen were in use in Frontinus' day, ranging from the *quinaria* (diameter 2.3125 cm) to the *centumvicenum* (diameter 23 cm). To complicate matters further, some four of these, but only four, were by convention actually a different size from what they were supposed to be. Worse yet, of the four, one was smaller and three larger than their nominal dimensions.[54] It is small wonder that Frontinus spent a third of his book sorting out the niceties of this situation, which, however, need not concern us in a general conspectus such as this. The nominal size of the *calix*, whatever it might be, was officially stamped upon it and a pipe of the same size connected to it, itself repeatedly marked with the same stamp for the first fifty feet to certify that it too was the correct size.

Such was the theory. In practice, opportunities for cheating were boundless, and, if we are to believe Frontinus, the Rome Metropolitan Waterworks staff were expert at all of them. The *calix* on a take-off line t received water from the tank, as fixed to the other end.[49] The the user could receive, and, in ce whereby his entitlement was based upon, and automatically able by continuous running, day that, since the whole Roman principle, and no doubt the f water rights, regarded water as waste, but as something he *l* to. At the same time, the an improvement by taking a ce; this is why the calix had to ead.[50] It was also specified that wing the *calix* had to be of the eared that if a large pipe was eck only a few inches long, it in reverse and unduly increase ated.[51]

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ortunities for cheating were nus, the Rome Metropolitan . The *calix* on a take-off line

Number	*Latin name*	*Diameter* digits	*Diameter* cm	*Circumference* digits	*Circumference* cm	*Area* sq. digits	*Area* cm²	*Capacity* quinariae
5	quinaria	$1\frac{1}{4}$	2·31	$3+\frac{267}{288}$	7·26	—	4·191	1
8	octonaria	2	3·696	6+[illegible]	11·611	—	10·728	$2+\frac{161}{288}$
12A	duodenaria	3	5·544	9+[illegible]	17·417	—	24·14	$5+\frac{219}{288}$
12B	duodenaria	$3+\frac{18}{288}$	5·659	—	17·779	—	25·151	6
20A	vicenaria	$5+\frac{13}{288}$*	9·323	$15+\frac{246}{288}$	29·29	(20)	68·265	$16+\frac{7}{24}$
20B	vicenaria	$4\frac{1}{2}$	8·316	—	26·125	—	54·315	13
40	quadragenaria	$7+\frac{39}{288}$	13·186	$22+\frac{5}{12}$	41·425	(40)	136·56	$32+\frac{7}{12}$
60	sexagenaria	8+[illegible]	16·144	$27+\frac{11}{24}$	50·71	(60)	204·69	$48+\frac{231}{288}$
80	octogenaria	10+[illegible]	18·646	$31+\frac{17}{24}$	58·58	(80)	273·06	$65+\frac{1}{8}$
100A	centenaria	$11+\frac{81}{288}$	20·847	$35+\frac{11}{24}$	65·495	(100)	341·33	$81+\frac{130}{288}$
100B	centenaria	12	22·176	—	69·668		386·24	92
120A	centenum-vicenum	$12+\frac{102}{288}$	22·83	$38+\frac{10}{12}$	71·724	(120)	409·35	$97\frac{3}{4}$
120B	centenum-vicenum	16	29·568	—	92·89		686·64	$163+\frac{11}{12}$

*By the system used for the smaller sizes, this should be exactly 5 digits ($20\times\frac{1}{4}$), but Frontinus has corrected it to bring it into line with the other system, so that the cross-section area is 20 square digits.

As stated in the text, Frontinus takes $\pi = \frac{22}{7}$, but in calculating the centimetre equivalents, the value 3.1416 has been used.

Where two sets of measurements are given, the first in each case (12A, 20A, etc.) is the theoretical value calculated by Frontinus, and the second (12B, 20B, etc.) the values used by the *aquarii*.

208. Table of *calix* sizes, as listed by Frontinus (J.G. Landels).

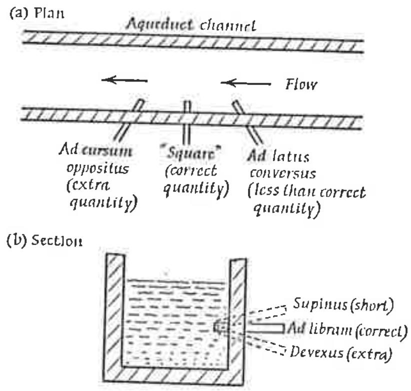
Roman size	Lead required per "10-foot" length (lb)	Lead required per "10-foot" length (kg)	Diameter, allowing for overlap (in)	Diameter, allowing for overlap (cm)
100-digit	864	392·25	22·6	57·4
80-digit	691	313·7	17·9	45·5
50-digit	432	196·1	10·9	27·8
40-digit	346	157	8·6	22
30-digit	259	117·6	6·3	16
20-digit	173	78·5	4	10·2
15-digit	130	59	2·8	7·2
10-digit	86	39	1·7	4·3
8-digit	72	32·7	1·2	3
5-digit	43	19·5	0·52	1·32

Overlap doubtful, so very approximate in this range

A 20-digit pipe required 1 ton per 125 ft approx.
1 tonne per 37·5 m

209. Table of standard lead pipe sizes (J.G. Landels).

might turn out to be a larger one than that authorised, where the gang installing the connection had been well bribed by the customer (or perhaps the better expression would be 'tipped').[55] The *calix* might carry the wrong stamp, or even no stamp at all. The use of a completely unapproved *calix* Frontinus considered the worst fraud of all since it implied the connivance of everyone, while the men installing an improperly stamped one could plausibly plead ignorance on their part. Again, the *calix* could be all right but an over-large pipe be attached to it causing the *calix*, so to speak, to work overtime (n. 51 above). There even might be no *calix* at all, with the supply pipe introduced directly into the *castellum* to draw off as much or little as the watermen pleased. The positioning of the *calix* was another source of trouble. Properly, it should

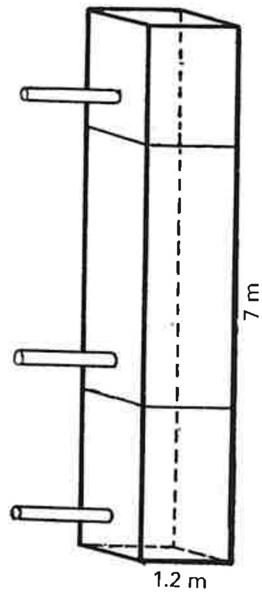


210. Effect of *calices* improperly set at an angle (J.G. Landels).

be set half-way up the wall of the tank into which it was inserted, and at a right-angle to the wall (Fig. 207). Not only will a *calix* set too low take in too much water, because of the head under which it is operating, but Frontinus was quite aware of the fact, and, at least partly, of the physics behind it.[56] Likewise, a *calix* not set straight would affect the volume of water it delivered. If it were angled to face the oncoming current in a conduit it would receive more than its due, and the opposite if it were facing away from it (Fig. 210). The volume would again be affected if the connected lead pipe sloped downhill or uphill.[57] It will be noted that while the point about low or high setting could apply to a *calix* sited anywhere, the angling relative to the current will affect only one set into a conduit with water running along it. Frontinus has just told us that placing a *calix* in such a position was prohibited, so there is a minor contradiction here. Possibly there were still plenty of old conduit-sited *calices* that had never been removed and which coloured his thinking. Strictly speaking, his words should be irrelevant, for they deal with an imperfect manner of executing an operation that is itself totally banned. And Frontinus says that his book is intended to set helpful guidelines for himself and his successors, so the question of the right way of setting a *calix* into a conduit should never arise since the thing was never to be done at all.[58] There were plenty of other abuses as well, such as claiming labour time for work not done, which were purely administrative in scope and need not concern us here. Only one final point need be made before we leave the *calix*.

The *calix*, I have said, controlled the distribution and consumption of the water. It also had a third function. It was the basic unit of measurement for the volume of water handled by the system, the term in which all estimates were expressed and on which all planning was based. More precisely, the smallest *calix*, the *quinaria*, was this unit, and was the only one used. Faced with a large figure one did not ascend to the use of a higher unit, as with cents and dollars, or inches and feet; and

Frontinus (II,64) can list the total capacity of all the Roman aqueducts as being 12,755 *quinariae* according to the official records, and 14,018 *quinariae* by actual measurement (i.e. the records were wrong). This has always caused grave problems. It is not just a question of 'How much water is a *quinaria*?' There are two problems. As a matter of practical engineering, how can a simple pipe be used to measure a volume of water? And, second, how can a linear measurement, the diameter of a pipe, be used to express volume? It is like saying, in modern terms, that a city daily consumes 15 six-inch pipes. The vital element missing, for a figure with any meaning, is time, or rate of flow (which is a function of it). Thus, a six-inch pipe running at five feet per second gives us that concept of volume that, without the time or speed element, we seek in vain. But nowhere in Frontinus, or elsewhere, do we find any reference to speed of flow, without which listing the cross-section or diameter of the pipe is idle and pointless.[59] This has sometimes led to complaints that the ancients did not even realise that the volume of water flowing through a pipe depended quite as much on how fast it flowed as how big the pipe was. The truth almost certainly was that Frontinus fully realised the importance of measuring speed of flow, but simply could not do it.[60] The ancient world, lacking any time-measuring equipment more precise than the water-clock or sundial, could not record speeds. The proof of it is that no set unit of speed, such as kilometres per hour, or feet per second, exists in Latin or Greek. With no way of measuring variation in speed, therefore, the only way a pipe could be used to measure volume was to standardise on speed of flow, so that it was always the same and the size of pipe, the only variable, therefore accurately reflected volume of discharge. On this principle, it will be seen, one did not have to worry about the actual speed of flow; as long as one could rely on it always being the same, it did not matter what it was. There was a simple way of doing this. Speed of flow through a submerged pipe in gravity flow (i.e. with no pumps involved) depends solely on the head. In other words, the speed the water flows out through a *quinaria calix* set into the side of a *castellum* depends on how far it is below the water level inside. This is purely a linear measurement, and can be measured with nothing more complicated than a foot rule. Provided one can therefore standardise the head, the *quinaria calix* will always discharge the same amount of water, and can thus validly be used as a unit of volume. This is almost certainly what was done. Purely as a pipe measurement, we know what a *quinaria* was. It was a pipe of 2.3125 cm diameter. Used as a measurement of volume, it was the amount of water that passed through such a pipe under a fixed, given head. What that head was, neither Frontinus nor anyone else tells us. It has reasonably been deduced by Di Fenizio[61] that it must have been, at an absolute minimum, at least 12 cm. A *quinaria calix*, or pipe, operating under this head, will discharge 40 m^3 per twenty-four hours, and this is accepted by most modern studies as what



211. Novae (Svistov, Bulgaria): lead distribution tank (Biernaka-Lubanska).

Frontinus and the Romans meant when they used *quinaria* as a unit of volume.[62] It must in closing be emphasised that all of the above material, relative to the *quinaria, calices*, their installation and their sizes, applies only to Rome itself. Other cities may have regulated their water in a similar fashion but we know little or nothing about it. All the evidence comes from Rome, and nearly all from Frontinus. That is, it is literary and not archaeological. Hardly any remains of *calices* have been found, and had not the one single manuscript of Frontinus survived,[63] this whole area of ancient water with all its sophistication and complexity would have remained unknown to us, perhaps even unsuspected. No other city handled anything like the volume of water provided by the eleven aqueducts of Rome; most had three or four as a maximum, and just one was quite common. It is quite possible, therefore, that other, simpler, means of water allocation may have been employed. For actual archaeological remains of the urban distribution system, easily our best source of evidence is Pompeii, just as our best literary source, Frontinus, represents Rome. But it is hard, and sometimes risky, to integrate the two to provide a generally valid overview, for there is no telling how far the watermen of Pompeii operated on the administrative principles of Frontinus, or whether the pipes of Rome were the same as those of Pompeii.

We now leave Rome, and turn to the secondary *castella*. So few have been found it is difficult to generalise about them, but in so far as their function was the distribution of water, presumably they were normally built at ground level. At Pompeii, where most of our known examples are to be found, they fulfilled another function as well, the control of pressure, and in pursuance of it were built on top of brick piers around 6 m high. These piers are to be found at strategic locations on street corners around the town – at Pompeii twelve of them have been identified – with a lead tank on top, forming the actual reservoir.[64] For such containers, lead was the normal material. Iron could not be used because of rusting, there being no galvanised iron, and in any case the ancient world could not produce the sheet metal needed for the sides of tanks: only lead could be poured out to form a flat sheet (see Fig. 215 below). We have already seen how, apart from pipes, it was also normally used to make the temporary conduits installed as local by-passes in case of repairs, and it was also used for distribution tanks inside houses. Particularly striking is the unique lead tank found at Novae, Bulgaria (Fig. 211).[65] It is used as a collecting tank at the springs serving the aqueduct, and is notable both for the fact that it is upright, much higher than it is wide or deep, and for its extraordinary dimensions – it is 1.2 m square and no less than 7 m high, and was apparently made in three sections, each with a single offtake pipe 18 cm in diameter and fitted with a perforated lead filter. The three sections were made separately and added one on top of the other, extending the tank upwards, apparently during two rebuilds, 'with', says its excavator, 'the simultaneous shutting one after another, of some of its outflows'. The Pompeii tanks were normally served by a large-diameter lead pipe running at surface level from the main *castellum* at Porta Vesuvii, and operating as an inverted siphon. On arriving at a secondary *castellum* (Figs 203, 204) this pipe climbed vertically up one side of the supporting pier, where a recessed slot to take it is often preserved in the brickwork,[66] and discharged into the lead tank. From the bottom of the tank – low down in the side or actually from its floor – smaller offtake pipes carried the water back down the brick pier and along the street to individual houses. The base of the pier was often found a convenient spot to locate a public fountain, directly served by one of the downspouts. A further refinement is urged by Kretzschmer, who carries the Vitruvian tripartite division also into the water towers. Public works (e.g. theatre, circus, nymphaeum), according to this scheme, are served directly from a single main[67] which is one of three coming directly from the primary *castellum*. The other two serve two completely independent sets of water towers; from one set of towers are served the public fountains, from the other the private users. There are thus two completely separate networks co-existing throughout the town.[68] This unnecessary duplication seems also to lack evidence, and I think we may assume that in the normal way each water tower served both private users and public fountains alike, in whatever way was most convenient.

The manner in which the water towers controlled pressure has been often misunderstood, though now clearly explained by Kretzschmer, followed by Eschebach (see Fig. 212).[69] The problem is the static pressure in the pipes of the urban distribution network. Some pressure is necessary, to get the water to rise as high as the taps in the houses or spouts in the street fountains, and there to issue in reasonable velocity and volume. On the other hand, one does not want too much. The reader will remember my insistence that pressure was not a governing factor in siphons and wonder why things should now be different. There are two reasons. One is that while Roman pipes could contain high pressure, Roman taps could not. There were no taps on siphons, so the problem did not arise, but on the city network the taps were the weak link. Static pressure in a pipe (or tap) is exerted equally in all directions. The construction of the tap was such that, though it could well resist pressure at the sides and the bottom, the top was weak. There was nothing really holding down the central rotating cylinder inside the body of the tap (see pp. 322ff. below on taps), and under pressure it would simply blow out through the top. Pressure, therefore, had to be held down to a level that the taps could cope with. Second, in the siphons high pressure was faced because there was no way of avoiding it. Had it been possible to reduce it no doubt the engineers would have done so; it would probably have cut down on leaks and put less strain on the joints; but since it could not be reduced, it was accepted and dealt with. The urban network, however, was different, for here a remedy was at hand.

The basic point is that pressure is governed by head, or the vertical column of water supported. The pressure in the pipes therefore depends on how far the pipes lie below what would be the natural level that the water in them would rise to, given the chance. For our purposes, this natural level is the level the water was actually at, the last time it was running in the open before plunging into the closed pipes, which in turn means the level in the main *castellum divisorium*. If this *castellum* is at ground level, pipe pressure will therefore not be high. The trouble comes if the city itself is not flat, but built on a slope, as so often happens. The aqueduct must, if possible, enter at the highest point of the city, so as to serve it all. The *castellum* will be located there too, and as the pipes branch out along the streets, they get progressively lower below it and the pressure in them increases. To take an example from Pompeii (Fig. 212), the ground level at the intersection of the Via Stabiae and Via dell' Abbondanza is 18 m below the *castellum* at the Porta Vesuvii, producing in the pipes a static pressure of 1.8 kg/cm^2.[70] This is quite enough to burst the taps and, in Kretzschmer's opinion, to harm the pipes as well. However, before it gets to the taps the water passes through one of these water towers. The tank on top of it being open, the water level in the tank now replaces that in the *castellum* as the factor governing pressure at the taps. There still *is* pressure, for the tank is raised some 6 m above ground level, but this produces a pipe pressure of only 0.6 kg/cm^2 instead of 1.8. It will thus be seen that the water tower does, in a sense, both reduce and increase pressure, and so Van Buren and Maiuri are both right;[71] it

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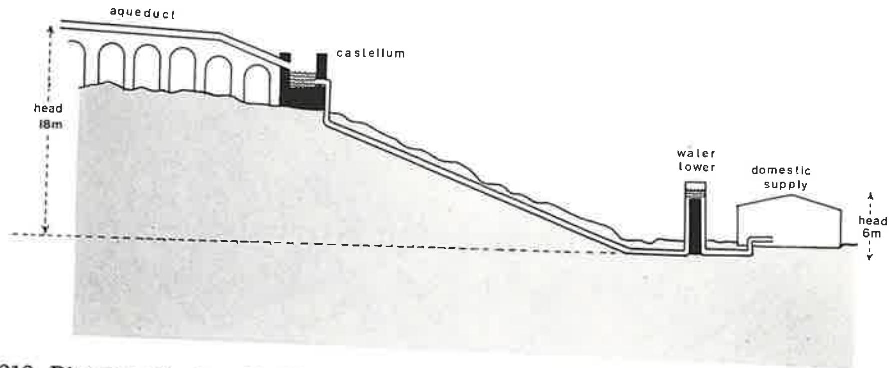

212. Diagram of urban distribution (based on Pompeii), showing how the use of water towers reduces the head governing pressure in domestic pipes from 18 m to 6 m (after Kretzschmer).

reduces pressure in that the pressure on the taps is reduced to that of a 6 m head instead of an 18 m one, and increases it in that by raising the tank on top of a pier one does provide enough pressure to serve the taps properly, whereas if the tank had been built at ground level there would be no pressure at all. Of course, as one looks at Fig. 212, the weakness in this system becomes apparent: if one has an open tank with a pipe running downhill into it, will not the tank overflow? This well exemplifies how the Roman system of constant offtake operates, for the only thing that stops, or can stop, the water tower overflowing, is if the water is constantly drawn off from it as fast as it flows in. A modern engineer thinks in terms of supply keeping up with demand. Here it is a question of demand keeping ahead of supply, otherwise the system will not work. The use of water towers to reduce pressure would not be necessary in a city that was completely flat, but in practice few such existed. The slope did not have to be very great to make its effect felt, and we encounter the Pompeii problem also at Nîmes, Arles, Vaison-la-Romaine, Trier, Metz 'und andere Römerstadt waren daraufhin zu studieren'.[72]