ANTİK ÇAĞDA SU YÖNETİMİ

MUNICIPAL WATER SUPPLY IN ANTIQUITY

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MAINTENANCE PROBLEMS IN ANCIENT AQUEDUCTS

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Municipal water supply in antiquity

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Summary

Since the beginning of early cultures men not only used natural water resources but also improved them by artificial methods. Based on observations of nature they constructed small and large storages for a temporary transfer of water from a period of rich supply to one with scarce supply but big demand. The method of a local transfer diverting water to the place of demand was also invented very early. The technological development especially of this kind of transfer is roughly outlined. Examples are given for the different elements of ancient water supply systems.

General

Each settlement of men depends on a sufficiant water supply. This applies especially for the arid and semiarid climate in the regions around the Mediterranean and the Near East where water is extremely scarce in summer. But in these regions the first cultures rose. In the following the main elements of municipal water supply will be presented as well as their artificial development by men including the combination of different methods. Examples will be shown from prehistorical up to Roman times.

Local Supply

The water demand of the first small settlements and villages probably was covered by local sources. Subsurface water could be used from perennial flowing rivers (i. e. Nile, Euphrat, Tigris etc.) or lakes. Naturally this water is and not seldom was contaminated. On the other hand water from springs often is much purer, cooler and it tastes better. Therefore it seems to be understandable that springs were mythically venerated, especially when they appeared in very dry regions. In general such springs were framed and a fountain-house had been constructed including a basin in order to enable the drawing of water by people. As an example the Gihon-spring in Jerusalem or the Castalia in Delphie may be mentioned. Fig 1 shows such a fountain-house of the spring Hagios Stratigos in Pergamon. The structure is 6,32 m long and 1,60 m wide. Four columns bear its roof. The water had been collected in an adit and led to the basin (Gräber 1913).
Of course the discharge of springs is limited. Therefore it is not astonishing that people tried to increase it. This for example could be done by seepage galleries, which were cut into the natural rock. Such a tunnel is described also by Gräber (1913) for ancient Pergamon. Two tunnels, one above the other, in two different but combined storeys collected the seeping water on a length

of more than 150 m and led it to a basin at the surface (Fig. 2). This construction at least functioned until the beginning of this century.

But not always the water necessary rose to the surface in springs. Often wells had to be dug into the soil or rock in order to meet an aquifer. If necessary the wells had to be strengthened by linings. Kienast (1981) describes the method of undermining the wellrings and thus sinking them. The mouth of a well was covered and provided with a top in order to facilitate the drawing of water. Fig 3 shows such a well-top in Aphrodisias (Turkey). The deep flutes are clearly to be seen which have been scratched into the marble by bucket ropes during many centuries of operation. The importance of wells for the water supply especially in rural regions is underlined by the laws of Solon (640-560 B.C.). He ordered that public wells could be used by the inhabitants within a radius of four stadions (about 740 m). Anybody who lived in a longer distance should dig a well for himself. Those people only who had dug more than eleven fathoms (about 11 m) deep without finding water should be allowed to draw a certain amount of water from the well of his neighbour two times a day (Merckel 1898).

Aspects of defense

Wars happened to be relativeley often since early history until the long period of peace in Roman times. People had strategic advantages when defending a settlement or a castle on top of a hill. Therfore castles, villages or towns often had been founded on isolated mountains since Mycenic times. The supply with water for human beings and animals was compulsory also at these places, especially in respect to the probability of being besieged for a long period of time. However springs, wells, rivers, or lakes are situated at the bottom of hills or in valleys. Therefore people had three possibilities for the water supply:

a) deep wells to be dug to the aquifer
b) cisterns in order to store precipitation
c) transfer of water from springs or subsurface sources

Deep wells

As an example for the water supply by means of deep wells the Athenian acropolis may be mentioned. Fig 4 shows the well and its fleet of stairs on which people could walk down in order to draw water. This well had been constructed in Mycenic times (Kienast 1982).

Cisterns

The second alternative is the storage of precipitation in cisterns, which are proved having been constructed in the whole region around the Mediterranean and the Near East since the 3rd Mill. B.C.. E.g. every house in Jerusalem had its own cistern. Very often they were cut pear-shaped into the natural rock with a small inlet being covered by stones or wooden plates. In Hellenistic and Roman times the number of cisterns built of stones increased. Not seldom the walls had been plastered in order to avoid seepage losses. Fig. 5 shows a cross-section of a cistern in Aspendos (Turkey). A landslide has cut it and thus the inner part can be seen.

The cisterns of the acropolis of Pergamon systematically have been surveyed and analysed by Garbrecht (1969). He also had tried to estimate the population of the early Hellenistic city from the possible water supply. For his calculation he assumed an average volume of each cistern, the same specific number of the cisterns per ha inside the whole city as in the upper part, the same climatic situation in antiquity as today, and a water consumption of 10 l/d per person. Under these circumstances about 20 000 people could have survived a besiege of one year. Thus it was proved that the cisterns were the backbones of the municipal water supply.

Local transfer

Sometimes the water to be stored was not led into cisterns but into open pools. Famous are the pools of Jerusalem which are partly mentioned in the bible. The realization of deep wells as well as cisterns was limited locally. The structures could be operated and maintained under the protection of the city walls. Thus the third alternative, i.e. the local transfer of water from a place outside of the city into it, meant by far an increased effort. As an example again may be referred to Jerusalem. King Hiskia ordered the construction of a tunnel in order to lead water of the Gihon-spring to the Siloah-pool inside the city. This happened around 700 B.C. during a war against Assyria and also is mentioned in the bible. The so called Hiskia-tunnel is well known. Its total length is about 530 m, although the direct distance between entrance and outlet amounts only to 370 m. These measures indicate, that the tunnel doesn't run in a straight line. In fact it is S-shaped in plan (Fig. 6). In the tunnel an inscription has been found informing us that the tunnel had been dug from both sides. As obviously no shaft existed it is still discussed today how the builders knew where they had been underground and how they had to dig in order to meet the other branch.

The principle of this water deviation was not new. E.g. the so called Perseia-spring in Mycenae also had been kept underground and its water led to a basin inside the city. However this basin was cut deep below surface. But from early history another conduit has to be mentioned as example for the local transfer. It is a pipe-line for the palace in Cnossos on Crete. As shown by Evans (1930) the water from the Mavrokolybo-spring was led in a conduit of taper-shaped terra-cotta pipes. However the importance in respect to science is, that in the course of the pipe-line a pressurized part existed, although the pressure was small. The fact that the principle of communicating tubes was applied in practice can also be proved by a fresco found in the palace. It clearly shows a fountain which postulates the application of a pressure pipeline.
Thus can be concluded, that in the 2nd Mill. B.C. all artificial elements to improve the water supply of settlements had been known and practiced, including the most difficult one, i.e. pressure conduits. The following development therefore was a technological one only not a scientific one.

Development in Greek Regions

The traditional cultures collapsed in the disturbances of the migrations around the 10 th cent. B.C.. Little evidence of hydrotechnical structures has been shown from the following epoch. Necropolises indicate that large settlements must have existed, but they are hardly proved. The same is true for water supply systems. Powerful city-states developed in Greece in the archaic epoch. An increased construction performance is evident in this era, also for the water supply. The systems being built had been of high standard although no technological development from poor to high level could be proved as Kienast (1981) pointed out. Therefore it remains an open question how far the knowledge and ability in Greece had been inspired from the neighbouring regions, especially from Asia Minor and the Near East. The water supply technology had further been developed with respect to industrialization in the following Classical and Hellenistic epochs. However this development had reached its peak with the Roman conduits, based on quite different technological achievements. The whole development will roughly be outlined.

Archaic Systems

The Eupalinos-conduit of Samos may be represented as an example for an archaic supply system. The fountain-house still is in use today and gives us an impression on this kind of element. The water of the spring had been collected in a triangular basin. Silt could deposit here. The basin had been covered. 14 pillars bore the ceiling, which again had been covered by earth in order to hide it from besiegers during war (Kienast 1979). The water flew from the basin into a pipe-line (inner diameter 25,5 cm) which was placed in a tunnel. Like many other archaic tunnels this most probably was a protection structure for the pipe-lines. The tunnel had been constructed like many others of a type like the so called quanates. From shafts, dug vertically into the rock, the tunnel had been cut horizontally to two sides. The length of this quanat-type tunnel is about 890 m. Then the famous Eupalinos-tunnel followed which is mentioned by Herodot (about 450 B.C.). This structure of 1040 m length is cut through the city mountain from two sides, i.e. from the north and the south. The southern branch runs straight while the northern one shows some bends in its course. A convincing explanation for these bends has not been presented yet. But it is evident, that Eupalinos knew always the position underground. Kienast (1979) identified 5 different longitudinal and 5 different horizontal measurement systems in the tunnel. Due to these measurements it was possible that both branches met in the middle. In the tunnel then another trench had been dug which changed into a seperate tunnel in the southern part. In this trench respectively tunnel the pipe-line had been installed. The whole system obviously was in operation for more than 1000 years. Fig.7 shows a cross-section of this structure.

The water supply system of Megara may be mentioned as an example of a conduit with a storage basin at its end. Two terra-cotta pipe-lines led ground- and springwater to a double reservoir of an area of 13,7 m x 17,9 m. In front of it and connected to it was another basin in order to draw the water from here. The ceiling of the reservoir had been born by 35 columus (Fig 8). The basin was thought of being that one mentioned by Pausanias (about 170 B.C.), the so called fountain-house of Theagenes (7.cent.B.C.) But Gruben (1964) proved, that it was younger. Anyhow the reservoir could store the discharge for daily regulations.

Hellenistic Systems

The technic for aqueducts had been improved in Classical and Hellenistic times. Costly tunnels in order to protect the pipe-lines were omitted. The single pipes were formed more advantageous with respect to their expenditure. After all this resulted from the steady increase of water demand because of the sharply increasing population. The demand was mainly covered by local transfer, i.e.by aqueducts.This may be shown at the example of the acropolis of Pergamon.

The first pipe-line had been constructed most probably in the era of Attalos I (241-197 B.C.). It was a single conduit. The pipes showed an inner diameter of 13 cm. The course was more than 20 km long. Near the acropolis a pressure-line was necessary with a pressure of 2 to 3 bar. Few years later a double pipe-line had been constructed in mainly the same line but on a slightly higher level. Therefore also a pressure-line was nessessary north of the acropolis. The inner diameter of the pipes measured 18 cm. The possible discharge of the second conduit was nearly 4 times as big as the first one. Again only few years later the third aqueduct had then been constructed, probably under the reign of Eumenes II (197-159 B.C.). It was a triple pipe-line from the Madrasdag-mountains in the north with a lenght of nearly 50 km (Fig 9). However the most important part was the pressure-line at its end having a lenght of 3,2 km. Fig 10 shows a view from the inlet basin to the acropolis. The maximum static pressure amounted to about 19 bar. The pressure-pipes had been of cast lead. According to Garbrecht (1978) the conduit had ended in between the palaces. The water then run to the main cistern. The overflow from there was led downhill from one cistern to the others so nothing of the valuable liquid was wasted. Thus the cisterns changed their task from a reservoir of caught precipitation into a storage of continously flewing water. The discharge of the total hitherto water supply system of the acropolis consisting of the cisterns, the single and the double pipe-line was doubled when the Madrasdag-conduit started operation. This aqueduct is proved having been operated for several hundred years.It is looked upon as peak of Hellenistic water supply technology.

Development in the Roman Empire

In general the Greek conduits have been installed subsurface as far as it is known from literature. For sure this was done because of safety reasons. Otherwise a visible conduit would have been cut by any besieger of a city. This had been modified in the Eastern Mediterranean not before Roman times, when Roman technology dominated in this region. It was developed in Italy obviously by the Etruscans. They used channels for irrigation and water supply and their knowledge was inherited by the Romans. Thus it is not surprising that the first conduit for the city of Rome, the so called Aqua Appia, was constructed as a channel in 312 B.C.. For this and the subsequent one, the so called Aqua Anio Vetus, it was still imperative being constructed underground . It was done in the quanat-method, described already for the first part of the Eupalinos conduit of Samos. Eventually, after the final destruction of its main enemy Carthage, people of Rome dared to construct a channel having a long section above surface, i. e. the Aqua Marcia. In the following time such sections, especially water bridges across valleys, became part and more or less symbol of almost all Roman aqueducts. This technology spread over the whole Roman Empire in the long period of peace, the Pax Romana.

Adits

Water was caught for many Roman channels in seepage galleries or fountain-houses like for Greek conduits. Both elements are proved for the Eifel-channel of Cologne. Fig 11 shows the so called Klausbrunnen, which has been restored by Haberey (1972). Water could flow into the basin through 10 slots in the walls. Due to the big cross-section in the basin the water moved slowly. Therefore any silt could deposit. Then the water discharged into the channel to Cologne. The outflow of the basin could be interrupted by a weir. The restored structure can still be visited today.

Contrary to the Greek the Romans used surface water from rivers or lakes also. River diversions had been constructed e. g. for channels of Side, Trier, Aix-en- Provence, Rome, etc. As diversion structure weirs had been built in antiquity like today. A trash rack was probably applied at the channel inlet in order to prevent floats moving into it. Fig 12 shows such a diversion structure at the beginning of the channel for Segovia (Spain).

The diversion of water from a dam is already mentioned by Frontinus (around 100 A.D.). He reports that the Emporer Trajan ordered the transfer of the diversion for the Aqua Anio Novus from the Anio river to the dam in the Anio valley near the town Subiaco. As Frontinus wrote, now pure water was discharged to Rom in this channel . The dam has been destroyed in 1305 A.D. No remains of it have overcome till today. However the diversion of water from a dam can still be seen in Merida in spain (Fig.13) As intake of the Cornalvo-dam a tower is erected as it will be constructed for earth dams today.

Dams as temporary transfer of the water supply had been constructed normally at the beginning of channels. However the pools of Salomon in the course of the aqueducts of Jerusalem show that even in the middle of a line a storage could be located. Fig 14 shows the downstream side of one of the three famous pools which is dated into the Hasmonean period, not to the time of Salomon (about 10 th cent. B.C.) as could be assumed by its name.

Channel

Behind the adit normally followed a channel as duct for the water. Three different principles seem to have been developed for the determination of its cross-section:

1.) Provision of a sufficiant area for the discharge
2.) Adherence of a nearly constant cross-section along the whole length of the channel
3.) Admittance and inspection of the channel from inside

The early aqueducts seem mostly beeing constructed by roughly cut stones set into loam (v. Deman 1934). Parts of the cross-section of the third channel of Rome, the Aqua Marcia, were built with carefully smoothed square stones. The newly developed limestone-concrete, the so called Opus Caementitium, and the mortar-technology prevailed at the construction of aqueducts in Caesarean times. At the aqueduct of Aix-en-Provence the impressions of the formwork are still to be seen at the walls (Fig 15). Obviously it had been constructed of poured concrete, as we do it today. The early channels had been covered by slabs which laid across the walls horizontally or gabled. Later the vault prevailed which was either poured over a scantling or being constructed over brick-slabs as lost form.

The channels had been impervious. This was gained by several different layers of plaster. They prevented cracks because of drying shrinkage or different temperatures (Malinowski 1978). We can respect only the results of Roman plastertechnology in constructing impervious channels over long distances.

The slope of the channels depended on the topographical cirumstances. If the difference between source and terminal of the aqueduct was small, the slope had to be minimized. This resulted in slopes of only e.g. 0,11 o/oo in a deviation-section for the Kaikos-aqueduct of Pergamon. These figures can only be looked upon as masterpiece of levelling.

Bridges

The water bridges of Roman aqueducts became very famous. According to Hecht (1979) they can be distinguished into walls (substructio) and arched bridges (arcuatura). Walls had been constructed in case the channel level was only a few meters above surface. Arched Bridges had been prefered if this height was more than 4 m to 5 m. The diameter of the arches and the pierwidth depended on the construction type (concrete, square stones) and the material available. A development from stone setting to concrete application can be shown for the construction of bridges as it was done already for the channels. The channel on top of the bridge had often been constructed in the same way as in its normal course below surface.

Very high bridges had been built in more than one storey. Criteria couldn't be proved for the dependency of the number of storeys from the structure height. The famous Pont du Gard (Fig 16) has three storeys at a height of 48 m, however the St. Antonin-bridge of the Aqua Anio Novus of Rome showed 4 arches above each other at a total height of 35 m only. The local particularities will have determined the layout of a bridge as individual structure like today.

Pressure-Conduits

In case valleys to be crossed were very deep pressure pipe-lines had been constructed also in Roman times. The principles for the construction looked like the Greek ones. The free flow aqueduct terminated in a transition basin which the pressure-conduit was connected to. This went downhill into the valley and rose on the opposite site again. There it terminated again in a transition basin to the following open channel. The difference to its Greek forerunners was the bridge, which often bore the pipe-line in the bottom of the valley. According to Vitruv (about 20 B.C.) the line should be kept here horizontally as long as possible. This could be achieved by a bridge. Remains of these substructures are known from many places of the Roman Empire.

The pipes had been manufactured from different materials. Very often lead- or stone-pipes had been used. However terra-cotta-pipes covered by concrete are also known, e.g. from Almunecar (Spain). Lead-pipes had been no longer cast, but manufactured from a plate, which had been bent around a cylinder and then soldered at the joint. Thus the width of the wall could be reduced. According to the measures and weights given by Vitruv the minimum width should be about 6 mm. The sizes of the pipes had been standardized. A first serie of standard measures is given by Vitruv, a second one by Frontinus (Fahlbusch 1982). The use of stone-pipes is known from many cities. Fig 17 shows parts of a pipe-line still in situ near Bethlehem from an aqueduct of Jerusalem. The single pipes showed male and female sockets. Their joints had often been sealed by a mixture of limestone and oil.

Terminal Storage

Water discharged continously into the cities. In order to avoid any waste a big cistern not seldom had been constructed at the end of aqueducts, e.g. at Lyon, Pergamon, Carthage, Rome etc. Here the so called Piscina mirabilis at the end of the aqueduct around the gulf of Naples may be presented. The volume of this cistern with 5 longitudinal and 13 cross-naves amounted to 12 600 m^3. The sinter-crust at the floor, piers, and walls proves the long operation for the navy at Cape Misenum (Fig 18).

Water Distribution

S.J. Frontinus describes in his two books "De Aqueductun Urbis Romae" besides others the distribution of water inside the city of Rome. However nearly nothing of this system has been found in the Italian capital. But archaeological evidents are known from other cities. The aqueduct terminated in a distribution structure, a so called castellum. Fig 19 shows the respective one which was found in Nimes (France). 13 pressure pipelines had been connected to the basin. Most probably they supplied the different parts of the ancient city and not different customers.

A number of draw-wells along a course of such a main urban pipe-line had to be filled up. In order to avoid the waste of water and to supply also other customers distribution towers had been applied as we learned from the excavations of Pompeji. Fig 20 shows a draw-well and such a tower. About 40 wells provided the population in Pompeji as far as it is excavated today. According to Eschebach (1979) people seldom had to walk longer than 50 m to get water. How many cities of today would be glad, if they had such a splendid water supply and distribution system.

Conclusion

As was outlined the different methods of improving the water supply of settlements have been invented very early. Basically no element has been added up today. However the technological skill has been improved steadily that world records in some fields have been achieved in antiquity for many, many centuries. The water supply of some ancient cities amounted up to several hundred litres per day and person, a number which today is provided for cities only in a few highly industrialized countries. The fact that the water supply system for many big cities in Central Europe had been constructed in the last century following to the Roman examples may indicate the high standard which had been achieved in antiquity. As engineers of the 20 th century we only can admire these achievements and hope that this standard will soon be gained worldwide.

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Fig. 1 Fountain-house Hagios Stratigos in Pergamon

Fig. 3 Well in Aphrodisias

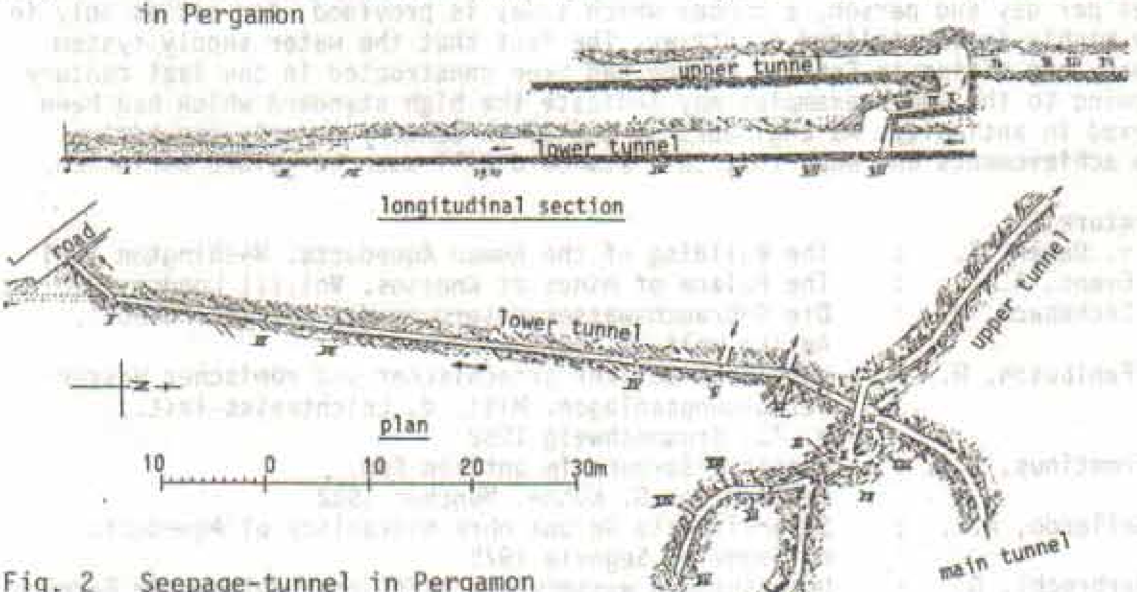

Fig. 2 Seepage-tunnel in Pergamon (Gräber 1913)

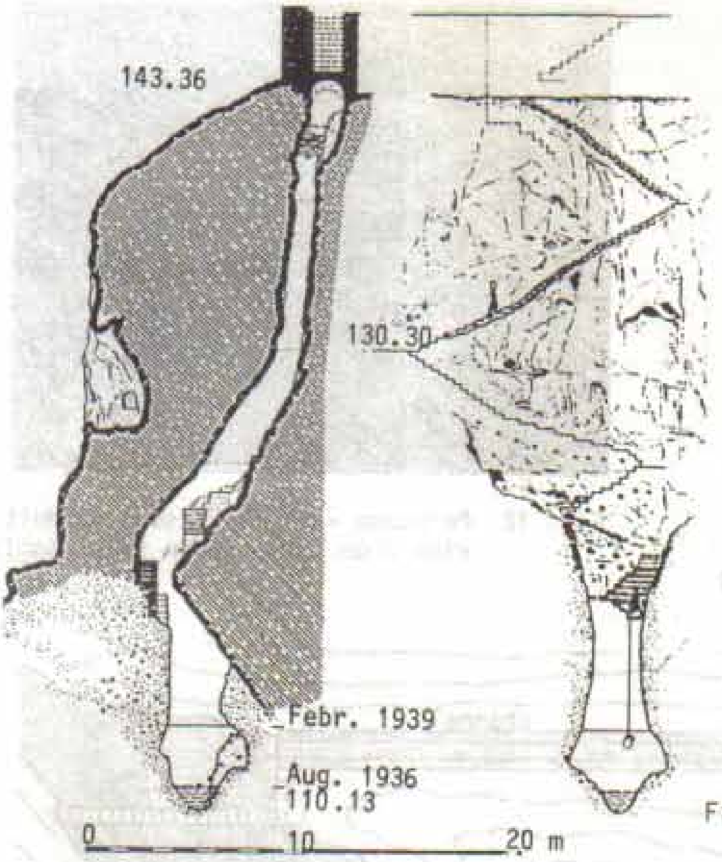

Fig. 4 Deep well in Athens (Kienast 1981)

Fig. 5 Cistern in Aspendos

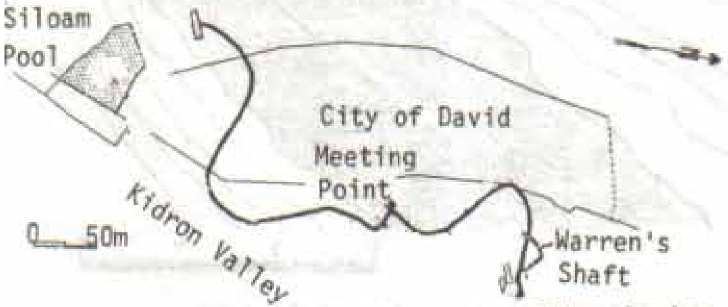

Fig. 6 Hiskia-tunnel in Jerusalem - Plan -(Kienast 1983)

Fig. 7 Eupalinos-tunnel of Samos

Fig. 8 Reservoir at Megara

Fig. 9 Pipes of the Madrasdag conduit of Pergamon

Fig. 10 Pergamon - High pressure conduit view from inlet basin to acropolis

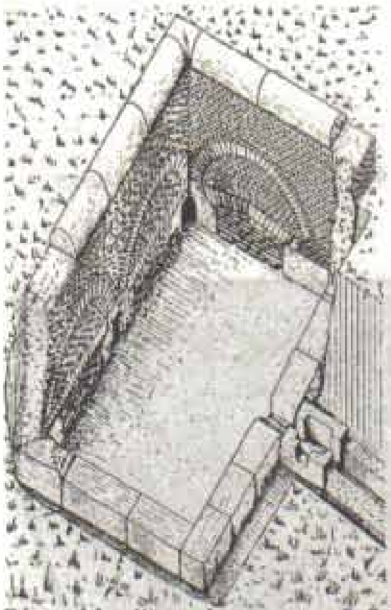

Fig. 11 Klausbrunnen of Cologne (Haberey 1972)

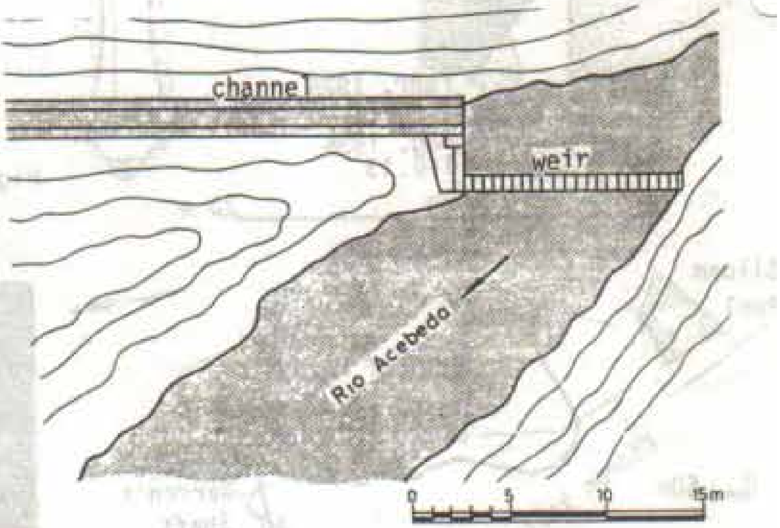

Fig. 12 River diversion at Segovia (Gallardo 1975)

Fig. 13 Cornalvo-dam at Merida

Fig. 14 Wall of Pool of Salomon - Jerusalem -

Fig. 16 Pont du Gard

Fig.15 Channel of cast Roman concrete -Aix-en-Provence-

Fig. 17 Pressure pipe-line near Bethlehem

Fig. 18 Piscina Mirabilis

Fig. 19 Distribution structure - Nimes -

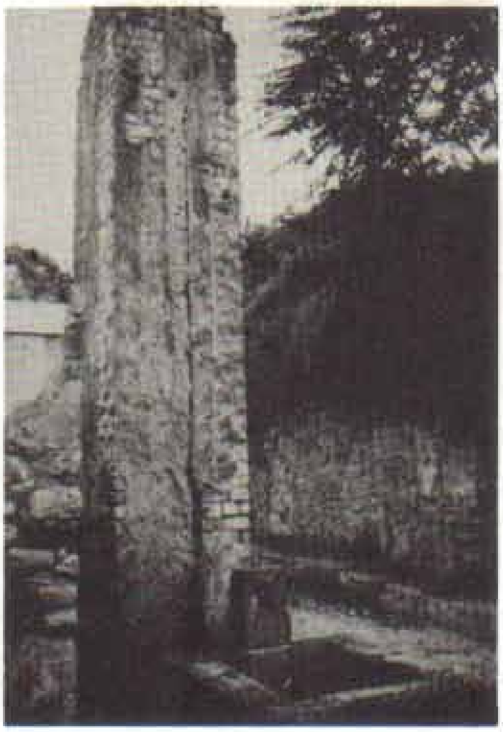

Fig.20 Draw-well and distribution-tower in Pompeji

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[Plates 1, 2, 3a]

General

Many studies have been carried out in the past to analyse the water supply system of different cities. Each system has its peculiarities, but because of the abundance of material a general scientific approach to the development of cities in antiquity as governed by their water supply is now possible.

However, one aspect of ancient water supply seems to have been neglected, i.e. the maintenance of the conduits. We know that water supply installations have to be carefully cleaned and maintained. Many inscriptions reporting these facts are known, e.g. the regulations mentioned by Frontinus.

Calcareous Crusts

In cases where an aqueduct was damaged, we may find archaeological evidence for repairs, though we are seldom able to detect the cause of the damage. Sometimes local cracks developed because of subsidence, sometimes because of earthquakes. Often poor masonry was the reason for similar damage. However, the deposits of calcium carbonate — the so-called *sinter* — threatened many aqueducts along their whole course.

Channels

In Roman times, at least, it was preferred to bring calcareous water in channels into many cities, because of its excellent quality. In the water dissolved limestone is present as calcium bicarbonate, which is soluble if enough carbonic acid (carbon dioxide) is present. This equilibrium, if disturbed by increase of temperature or turbulence (such as by aeration), will shift toward the disappearance of the excess carbonic acid. Thus, calcium carbonate will again precipitate. The precipitation is more likely to occur at rough spots or at points of turbulence in the conduit. This deposit, or sinter, will slowly form a crust on the bottom and walls of the conduits, reducing the cross-section free to carry the water and increasing the roughness of their surface. As long as they were free flow channels the deposits resulted only in a raised water level, which is the reason for the curved shape of the wall-sinter which can be observed in many Roman channels.

Naturally the sinter crust had to be removed if it became too thick, and Frontinus reports on that kind of work in Rome's aqueducts.[1] It has been proved that the crust in the aqueduct of Aspendos has been removed at least five times.[2] As this work obviously had to be done regularly, the constructors thought about a method of reducing the necessary labour of chiselling the sinter. This was achieved by careful polishing of the plaster on the walls and bottom and an additional coating of lime, to stop the sinter from adhering to the plaster and building up on it. Naturally the hard work of chiselling could only be carried out in accessible channels with high cross-sections. This is why so many Roman aqueducts, where the discharge was small and the water only a few centimetres deep, were built with so large and high a conduit; it was to give room for the regular, essential maintenance work.

The removal of sinter in free-flow channels was necessary at regular intervals. These intervals were infrequent, sometimes only once in decades, depending on the thickness of the yearly layer of deposit. About 1-2 mm per year has been observed in aqueducts at Nîmes,[3] Pergamon,[4] and Cologne.[5]

Pressure-Pipelines

However, the situation was quite different when the water had to flow through a pressure-pipeline. Because the pipe had to flow completely full any layer of deposit would reduce the cross-section available by the square of the reduced diameter. The consequence was that the sinter had to be removed more often from pipes than from channels. As long as the pipes consisted of lead this was easy. Theoretically they could be cut, then the crust broken out, and afterwards the pipes soldered again. The pipeline was thus quickly restored to operation.

However, in most of the Roman long-distance aqueducts — especially in Turkey and the East — when pressure-pipelines occurred, they were made of stone. When sinter deposits formed inside such a pipeline (as, for example, in the twin pressure-pipelines of Laodikeia in Anatolia, shown in Plate 1a, where the very thick deposits are clearly visible), it was not easy to remove them. The pipeline was formed by a series of individual, square, stone blocks, which were drilled through and then joined end to end by male/female sockets. To get at the obstructing deposits inside, the entire pipeline had to be taken apart, each block cleaned out separately, and the whole then reassembled. This, as its only source of water, this method could not be used. Some alternative procedure would have to be devised, which did not entail dismantling the pipeline, and would keep to a minimum the time for which the water was cut off.

Chemical Maintenance

This goal, removing the sinter in a short time, could be achieved chemically, by using an acid to dissolve the sinter incrustation. The only acid which was both strong enough and available in antiquity in large enough quantities, was obviously vinegar.[6] We shall first assume that vinegar actually was used in the maintenance of pressure-pipelines, and shall try to reconstruct the procedure. We shall then turn to the archaeological evidence and look for anything supporting or verifying our hypothesis, the most relevant sites being the inverted siphons at Laodikeia and Patara.

Vinegar could be produced from wine with a concentration of up to 15% and it reacts with sinter only very slowly under normal conditions. When heated, however, the reaction is very greatly accelerated, and boiling vinegar, roughly speaking, reacts upon sinter 250 times more quickly than it does at a temperature of 20°C. If this chemical treatment were used, therefore, boiling vinegar would be needed so as to keep down the time the water flow was interrupted.

The de-sintering procedure would thus consist of four steps:

1. Cutting off the flow and emptying the inverted siphon.
2. Filling the pipe with hot vinegar and letting it react with the sinter inside.
3. Draining off of the sludge-like mixture of sinter and vinegar.
4. Refilling the pipeline with water and re-commencing normal operation.

The first step is easily done. The flow could be shut off at the intake basin by a sluicegate or valve. The conduit then had to be drained through a drain-hole at the deepest point of the pipeline. A stone pipe-section carrying what could be such a drain-hole has been found at the pressure-pipeline of Patara on the south coast of Turkey (Plate 1b). But this is not all. For the system to work, there also has to be an air valve located immediately after (i.e. on the downstream side of) the cut-off sluice at the beginning of the siphon. Unless there is such a valve or vent to admit from above air replacing the water as it is drained off below, it will be impossible to empty the pipeline completely. Weber (1898) mentioned a stone with a bore-hole that could act as such a valve, which he found beside the intake valve of the pressure-pipeline at Laodikeia.[7] (Fig. 1)

Next the pipeline had to be filled with heated vinegar, and to do this the stone pipes had to be pierced with vertical filling-holes. If a pipeline several hundred metres long was filled only from both ends, by the time it was

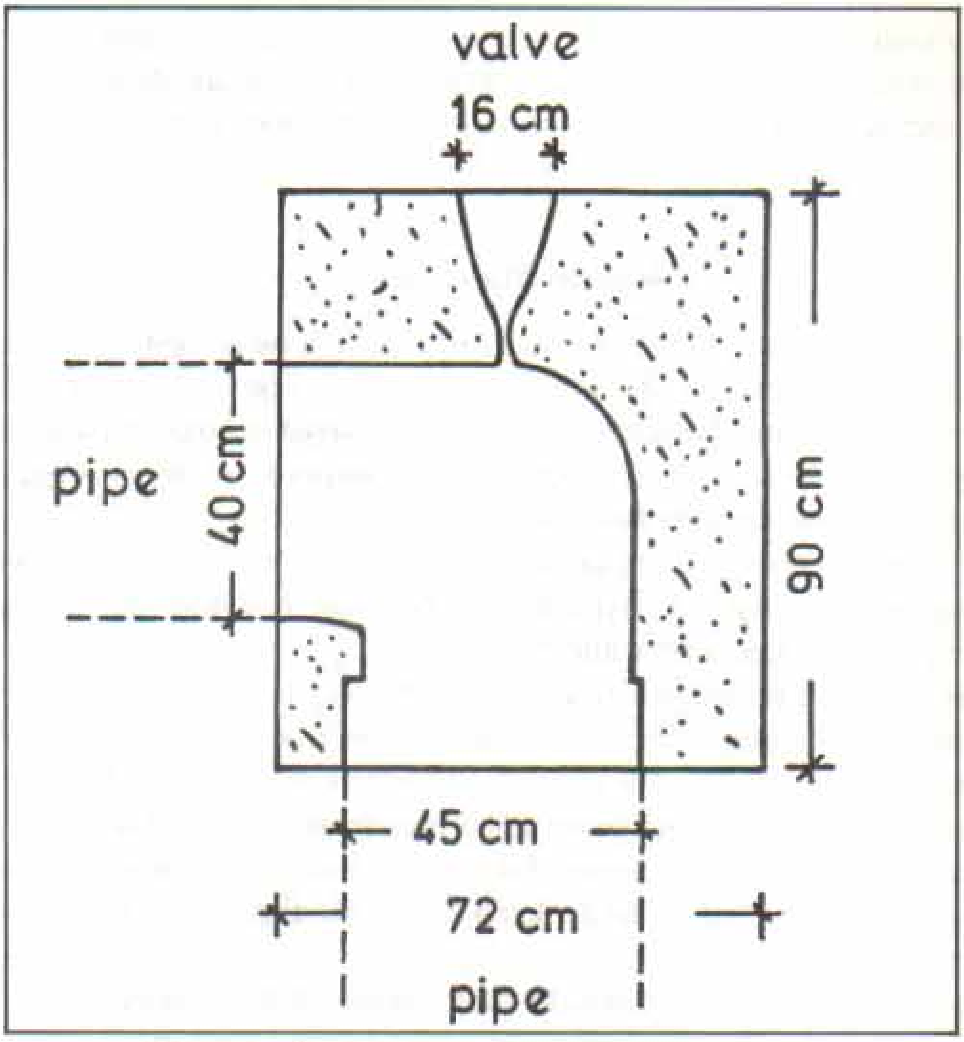

Fig. 1. Stone pipe with valve (?) for ventilation, from Laodikeia (Weber 1899).

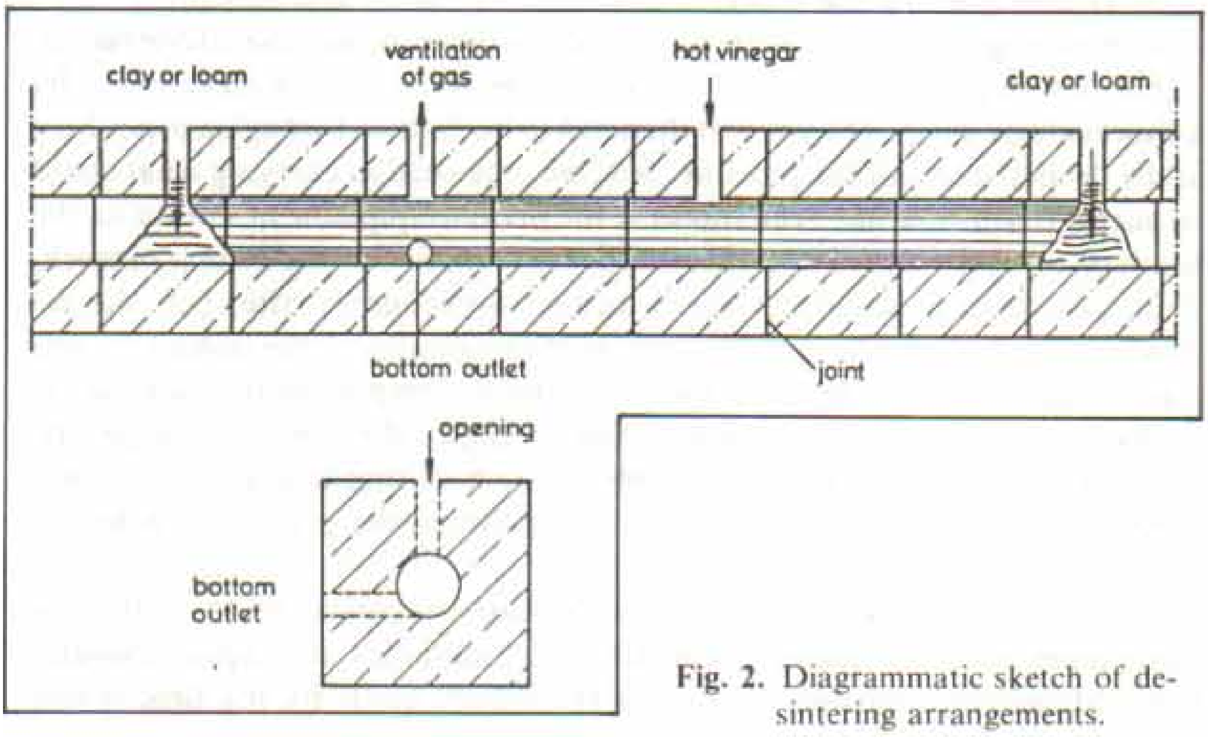

Fig. 2. Diagrammatic sketch of desintering arrangements.

completely filled the vinegar would have become cold; furthermore, the quantity of vinegar for this one treatment would be enormous. The answer to this problem, therefore, would surely be to divide the entire pipe-line up into a series of segments, which could be isolated from each other and treated individually.

To isolate any given segment, it would be necessary to plug the main bore of the siphon pipe at the end of the segment, so as to confine the vinegar to the section to be treated. The simplest way of plugging the bore would be to block it temporarily with, e.g., clay, and since two plugs would be needed, this would mean two holes, or openings, for their insertion (see Fig. 2). A third hole would then be needed for pouring in the vinegar, and a fourth to allow the escape of the gas generated in the first chemical reactions of the filling procedure. This gives us a total of four holes per segment, with perhaps also a fifth opening into the bottom of the conduit as a drain hole or bottom outlet, to drain off the sludge at the end of the treatment.

The lengths of the segments would vary, depending on whether they were located on the sloping sides of the siphon, or on the more flat central section, the "venter" as it was called by Vitruvius.[8] On this flat section the only factor governing the length of each segment would be the amount of boiling vinegar that was conveniently available for pouring in. At Laodikeia stones of this section are all collected together at one spot, and according to Garbrecht[9] five blocks out of 104 show the required boreholes, i.e. approximately every twentieth block was thus perforated. On the slopes, however, the segments would have to be much shorter, for the vinegar, being confined not in a level bore but in one sloping downhill, would press with much greater force against the lower plug; indeed, if the segment was too long, the hydraulic pressure on the lower clay plug would probably burst it. Therefore the distance between the boreholes had to be shorter, and indeed, at Laodikeia, out of 39 stone pipes lying still in situ on the southern slope, twelve are perforated, i.e. nearly every third block shows a bore hole drilled in from the top (Plate 2a).

All this archaeological evidence does seem to support the view that segments of the pipeline were treated with hot vinegar in order to remove the calcareous deposits. At Patara many blocks with boreholes were found, but none were on the slope. Instead, at the southern end of the slope was what was probably a sluice; it is obvious that the stone blocks forming the pipe enclosed some kind of a metal box (Plate 2b), and a similar arrangement can be found on the opposite slope (Plate 3a). Most probably it was the guide-stone to accommodate a sluice-gate, which at Patara would perform the same isolating function that we have elsewhere assigned to clay plugs. This was made possible by the fact that at Patara the slopes were relatively short, so that the hydraulic pressure brought to bear by the vinegar confined within the slope was low enough for a sluice-gate to sustain it: it can be calculated that of water some 25 m high (Fig. 3). It would appear, therefore, that for the chemical maintenance procedure outlined above, no boreholes would be necessary on the slopes that were relatively short.

The third step in the procedure was also easy. The inlet valve was opened again, and the muddy sludge of vinegar and dissolved sinter would be flushed out through the drain hole at the bottom of the siphon. In the final stage, all openings were blocked and the siphon put back into normal operation.

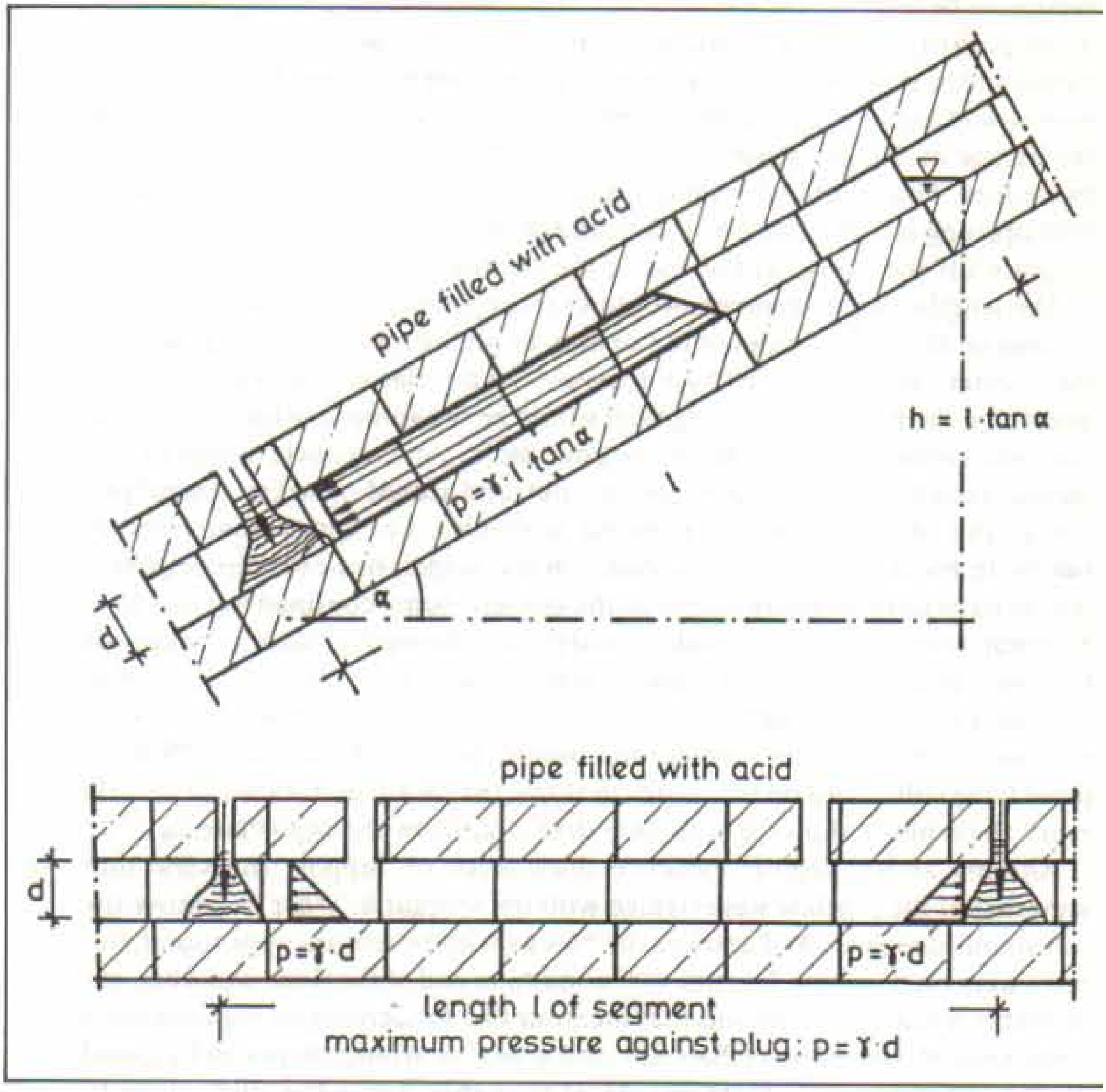

Fig. 3. Comparison of hydraulic pressure against a clay plug in horizontal and sloped segments.

Materials Required

The above hypothesis has outlined how stone pressure-pipes could have been maintained and their sinter removed through chemical means. But, it will have occurred to the reader, there is one outstanding objection — the huge quantity of vinegar necessary to do the job. Here, however, we must not be misled. When we look at photographs showing the layers of incrustation in Roman pipes or aqueducts, it naturally strikes us that it would indeed require a great amount of vinegar (and time too) in order to dissolve so thick a crust. We must remember that in such pictures the crust is so thick only because we are looking at an aqueduct at the end of many decades, centuries even, of neglect. It never would have — or at least never should have — looked like this in the Roman age, when it was being properly maintained. The secret of good maintenance surely was to clear out the incrustation every year or two, when it was only a millimetre or so thick, and could quickly be removed. From Neuburger,[10] it appears that 2.5 litres of pure vinegar is required to dissolve 1 kg calcium-carbonate. Therefore for a pressure-pipe of 30 cm diameter, about 6 litres of pure vinegar would be needed to dissolve a sinter crust 1 mm thick, which we can safely assume to be about one year's deposit. In order to fill up the pipe completely, about 70 litres of vinegar of 8.5% concentration would be necessary. Thus, for the twin pipe-line of Laodikeia, which was about 1,500 m long, close to 200,000 litres of vinegar of this concentration would be needed annually to keep it clear of sinter.

This really does seem a lot. However, assuming a population of probably around 10,000, it works out that 20 litres of vinegar per person per year would have been required to keep clear this vital bottleneck in the city's water supply system. And though this still may seem like a lot of vinegar, let us remember that vinegar is produced from wine. Surely — at least in an area where grapes are the main fruit cultivated — the equivalent of 20 litres of wine per year is not an unreasonable contribution to seek for so important a purpose: The maintenance of water supplies.

Summary

Regular maintenance of the aqueducts was necessary, especially where the water left calcareous deposits. It was not hard to remove this incrustation from conduits where the cross-section was quite large, but in stone pressure-pipelines special methods were required. In theory, chemical treatment was possible, and this hypothesis can be supported by archaeological evidence. For such a treatment, the use of vinegar, especially when heated, could have been eminently practical. Any constructive criticism of this theory will be welcomed.

NOTES

1. Sex. Julius Frontinus, *De aquaeductu urbis Romae*, 122, trans. G. Kühne in *Wasserversorgung im Antiken Rom* (München, 1982) 127.
2. H. Fahlbusch, 'Vergleich antiker griechischer und römischer Wasserversorgungsanlagen,' *Mitteilungen des Leichtweiß-Instituts*, Heft 73 (Braunschweig, 1982).
3. J.-C. Gilly, 'Les depots calcaires de l'aqueduc antique de Nîmes,' Ecole Antique de Nîmes, *Bulletin Annuel*, 6-7 (1971/72) 61-72.
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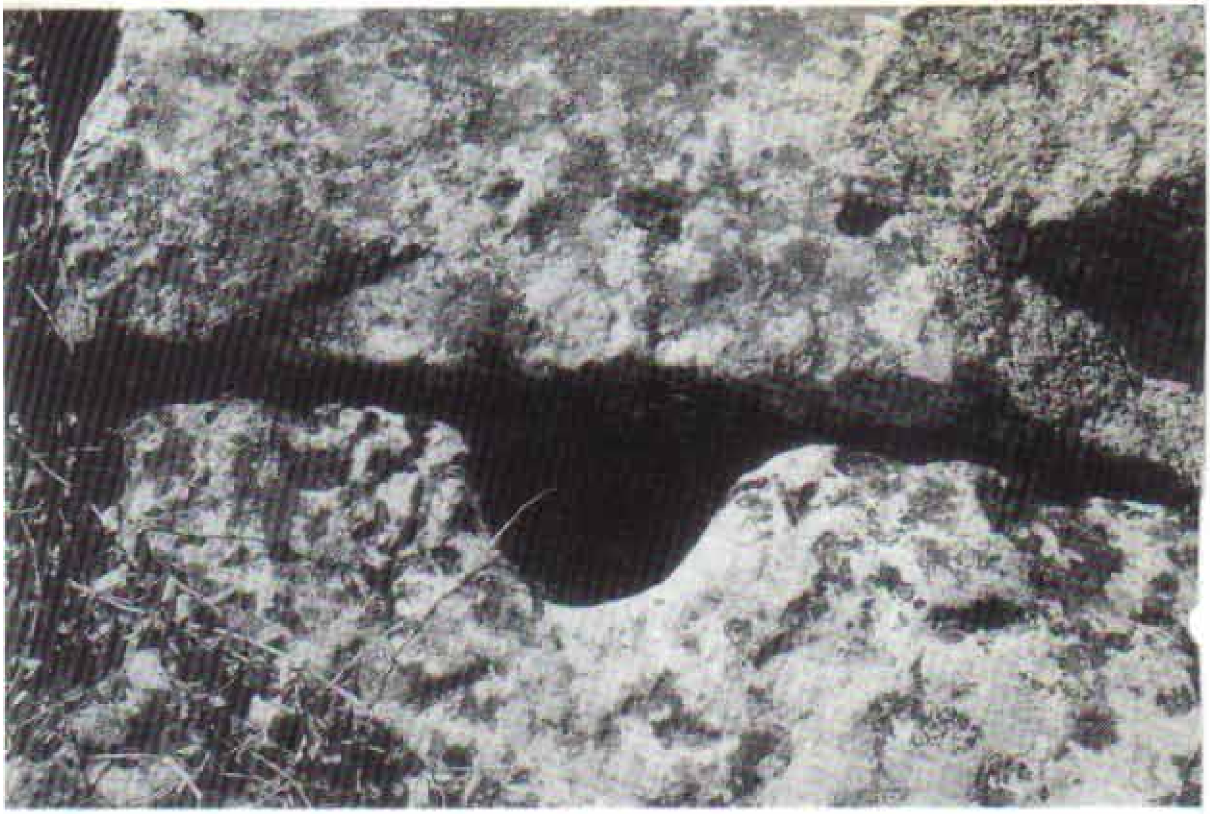
5. H.D. Schulz, 'Schichtungen im Kalksinter der Römischen Wasserleitung nach Köln. Eine Hilfe zur relativen Datierung,' in K. Grewe, *Atlas der römischen Wasserleitungen nach Köln* (Köln, 1986).
6. R.J. Forbes, *Studies in Ancient Technology* Vol. III (Leiden, 1965) 78.
7. G. Weber, 'Die Hochdruckleitung von Laodicea ad Lycum,' *Jahrbuch des Deutschen Archäologischen Instituts* (1899) 1-13, Pl. I.
8. Vitruvius, *De Architectura* 8.6.5, trans. C. Fensterbusch (Darmstadt, 1964).
9. G. Garbrecht, personal communication.
10. A. Neuburger, *The Technical Arts of the Ancients* (New York, 1930; trans. from *Die Technik des Altertums*, 1919) 461.

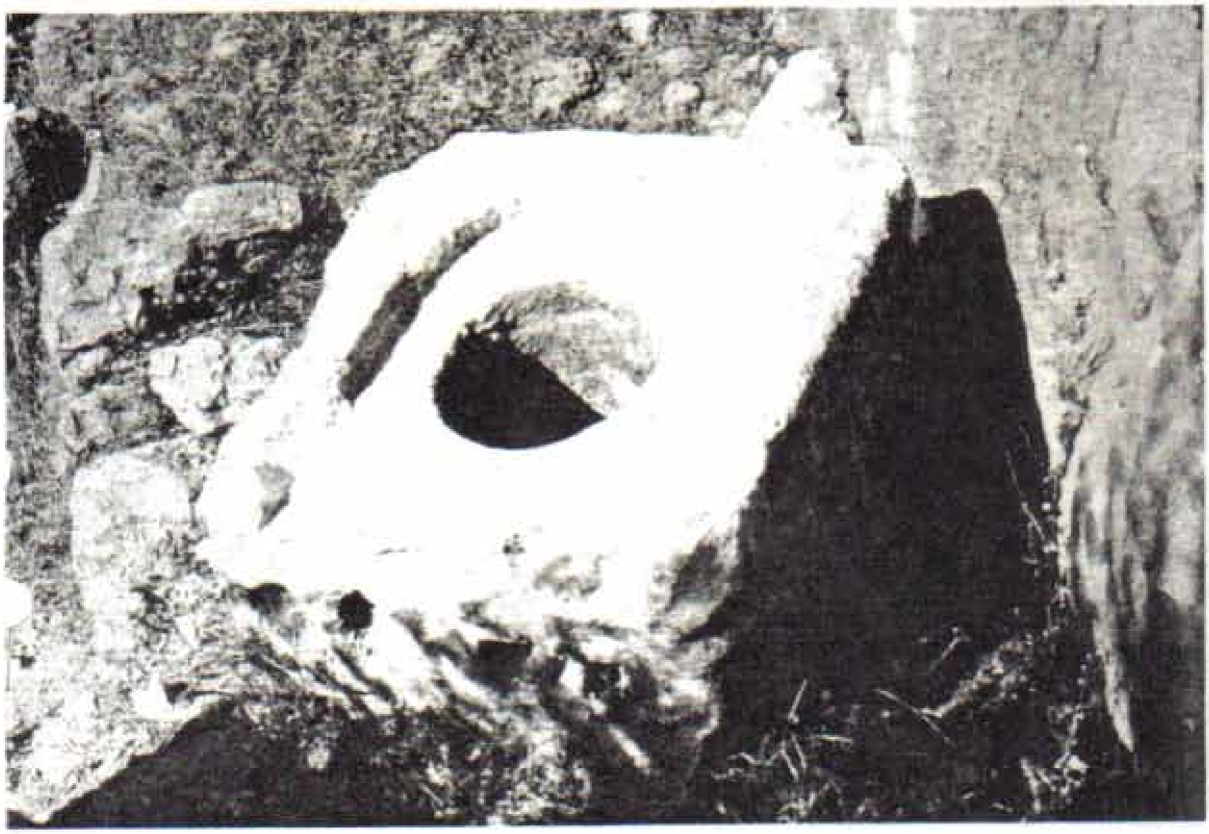
1 a. Laodikeia: sinter incrustation in the twin pressure pipeline (Fahlbusch)

1 b. Patara: stone pipe block with bottom outlet (?) (Fahlbusch)



2 a. Laodikeia: hole drilled in joint between blocks of stone pipeline (Fahlbusch)

2 b. Patara: recess for metal sluice (?) at southern end of sloping section of stone pipeline (Fahlbusch)



3a. Patara: guide-stone for a sluice-gate (?) to shut off water (Fahlbusch)

3b. Lyon: Garon (Soucieu) siphon, header tank; reconstruction showing manhole (Hernoud)