GeoJournal 11.3 207–213

0343–2521/85/0113–0207$1.05

Ancient Urban Water Supply Systems

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Abstract: Water supply systems were important components of early urban settlements. Because of frequent invasions, much thought was given to develop an enemy-proof and reliable water supply system for a city. *Sinnōrs*, or water tunnels, were used in Palestine prior to 1200 BC.

Qanāts were used in many areas for ground water utilization. A qanāt is an artificial underground channel which carried water over long distances, either from spring or from a water-bearing strata for irrigation and domestic consumption. Qanāts were probably first used in Armenia, from where they rapidly spread to many Middle East countries.

Fairly detailed information is available on urban water supply systems during the time of the Roman Civilization, a period which extended from about 100 BC to 200 AD, from the writings of Vitruvius and especially Frontinus, who was the *curator aquarum* of Rome. Frontinus made a state-of-the-art review of urban water supply systems, which is now the primary source of information on technology and practice prevalent at that time.

Introduction

Water is essential for human survival. Early man very quickly realized that without water bodily functions cannot continue for any prolonged period of time and that food — both from agriculture and animal husbandry — cannot be made available without water. In addition, watercourses could be used for transportation, which was an important consideration, since both road systems and forms of energy available for transportation were primitive. Accordingly, it is not surprising that the ancient civilizations grew up along the banks of major rivers like the Indus, Euphrates, Tigris, and Nile.

As human civilization began to evolve and population continued to increase, centres of population concentration began to form. While these early centres are not comparable with the present day urban areas, either in terms of the number of people involved or the extent of area covered, these were nevertheless forerunners of modern cities and towns.

As to be expected, water supply systems were important components of such early settlements. There are many instances during this early period, when invaders attempted to cut off the water supply systems of the cities in order to win battles by forcing the inhabitants to surrender through thirst. Thus, even though a settlement was well fortified, and citizens were safe from an invading army, it was imperative that the town had a reliable water supply system which could not be disrupted by the enemy. Accordingly, much thought was given during the early times to develop an enemy-proof and reliable water supply system for a city.

Asian Underground Water Supply Systems

Sinnōrs of Palestine

Sinnōrs, or water tunnels, were used in Palestine prior to 1200 BC. The cities in Palestine and Syria were usually built on the tops of hills, at the bottoms of which where streams providing the municipal water supplies. Thus, during times of war, cities were rather vulnerable because invaders could easily cut off the supply of water from the city. To protect the city, first a tunnel (sinnōr) was dug, one end of which provided a secret approach to the stream. Its other end was located within the city's boundary. Entrance to the sinnōr was gained by a shaft provided with a flight of stairs. In later versions thereof, a conduit on the floor of the tunnel brought water from the stream to the base of the shaft (Forbes 1955).

Fig 1 shows the Siloam sinna constructed by King Hezekiah around 700 BC near Jerusalem. According to the Second Book of Chronicles, the King also "stopped the upper watercourse of Gihon, and brought it straight down to the E side of the city of David". The 533m long tunnel, cut through limestone, conducted the water of the Gihon well under the city wall into the city proper. The tunnel is still in use today.

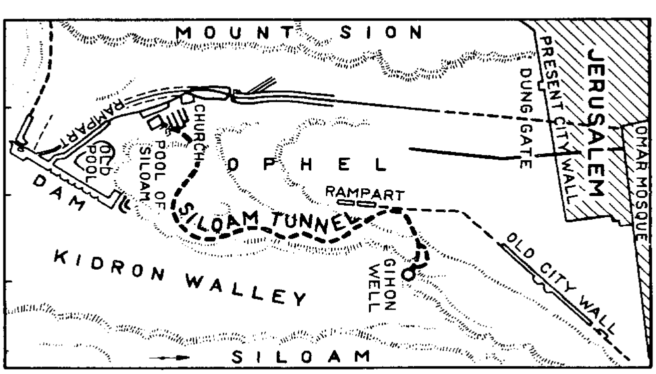
Qanāts

Undoubtedly the greatest achievement in the utilization of ground water of ancient times was the building of *qanāts* (or *kanāts*). A qanāt is an artificial underground channel (infiltration gallery) which carries water over long distances either from a spring or from water-bearing strata for irrigation and domestic consumption. Derived from a semitic word which means "to dig", it is also known as *iyn* in Saudi Arabia, *karej* in Pakistan, *falaj* in Oman and *sahzidj* in Yemen. Qanāts solved several problems in water resources engineering. First, evaporation was undoubtedly a major problem in hot and arid climates, and hence, with the limited water supply, surface water transport was a distinct hazard. Secondly, it was difficult to maintain a uniform slope in a hilly country; and finally, qanāts kept water cool and free of surface pollutants. Fig 2 is an aerial photograph of qanāt systems originating in the talus deposits at the foot of a mountain near Kashan in Iran.

S of Dizful in Iran is one of the old qanāt systems. It consists of three pairs of tunnels taking water from the gravel bars near the River Ab-i-diz, about 110km N of Dizful. Two pairs of qanāts supply water to the neighbouring land for agriculture, and the remaining pair supplies the city. These qanāts are at such a depth that some houses in the city extend six stories below the ground level to tap the water.

Contrary to popular belief (Amin et al. 1983; Kamiar 1982), the practice of qanāt construction probably originated in Armenia (Forbes 1955; Lehmann-Haupt 1910) and not in Iran. In his invasion of Urartu (present Armenia), King Saragon II (721–705 BC) of Assyria destroyed the irrigation network of the town of Ulhu. He described the irrigation system of the vanquished King of Ulhu in these terms: "Following his ingenious inspiration, Ursa, their King and Lord . . . revealed the water outlet. He dug a main duct which carried flowing waters . . . waters of abundance he caused to flow like the Euphrates. Countless ditches he led out from its interior . . . and he irrigated the fields" (Lassøe 1951).

Fig 1 Plan of Siloam tunnel (courtesy of Nils Borg)



The construction of qanāt, which according to Tolman (1937) was "the greatest waterworks of the ancients", was directed by an engineer called *muqanni*, who first located the water-bearing strata by digging a number of test wells. When a good stratum was hit, a mother well was dug. Another well was dug some distance away, usually about equal to the depth of the well, and the two wells were connected by a tunnel. By this procedure the construction continued. The direction and depth of the tunnel was determined by means of a crude but adequate system of plumb bobs. Fig 3 shows a typical water supply system by qanāts; the cross-section was somewhat egg-shaped. Since digging through rocks was a difficult process, the routes of the qanāts had numerous twists and turns, and large deviations were also made around hills. Only one man could dig at one time, and the excavated material was removed in a goat-skin bag through vertical air shafts. If necessary (depending on the soil conditions), lining materials were carried in the same bag on the return journey. As reflected light was used for digging, and working conditions were rather grim, one could expect that accidents would be rather common and loss of lives frequent. Details of qanāt construction have been discussed in detail by Biswas (1970) and Wulff (1968).

During the time of Darius I (521–485 BC), his Caryandan Admiral Scylox went to the oasis of El Khargeh (Caton-Thompson and Gardner 1932) in Egypt, and there introduced the qanāt system of irrigation. Butler (1933) believed that they must have extended far enough eastward – in fact under several hundred kilometres of rolling desert – to intercept seepage from the Nile. Later investigations, however, have clearly indicated (la Moreaux 1968) that the trace of the qanāts can be found from discharge point back toward the intersection of the water table in the talus slope of the escarpment of the plateau, a distance of about 3km. Traces of it can be followed very easily by the vertical air shafts connected with the main ditch.

As to be expected, the cost of qanāt construction varied with soil and terrain conditions. Beckett (1953) estimated that the cost of an average qanāt of about 10km in length was around $13,500 to $34,000. English (1968) estimated that the cost of the Kerman qanāt in Iran, 40km long and having a 90-m deep mother well, would be around $387,000. Increased agricultural production and sale of water could return 10% of the construction cost per annum.

Fig 2 Aerial photograph of qanāt systems in Iran

Use of these long infiltration galleries to tap ground water from soft sediment rocks or alluvial fan deposits quickly spread from Armenia to as far as Baluchistan in Pakistan. The qanāt used the principle of gravity flow. Its average length in desert regions was 40 to 45 km. It had a gentle slope of 1 to 3 on 100. In some places it had a depth of nearly 120 m (Feilberg 1945). Considering the state of hydraulic engineering and construction technology during the period in question, it was no mean achievement.

Water Supply during Roman Civilization

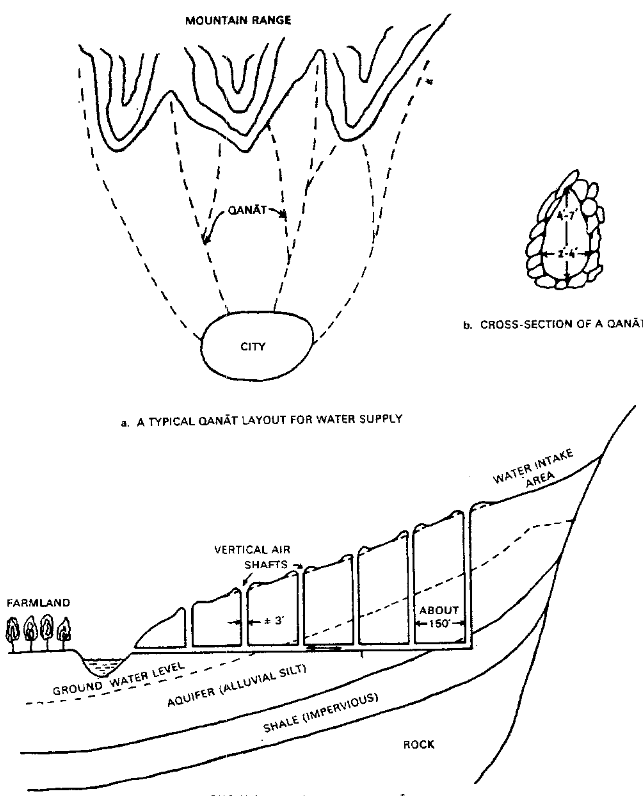
Fairly detailed information on urban water supply systems is available during the time of the Roman Civilization, a period which extended from about 100 BC to the end of the second century AD. The period could perhaps be best called the Greco-Roman Civilization, because the Romans had relatively very few new independent concepts to offer, even though they managed to build magnificent aqueducts, remarkable sewer systems, and a very fine harbour. Even during the peak of the Roman Civilization, the language of learned men was Greek.

One can say with some justification that the Romans were practical people. For example, their awe-inspiring aqueducts were built without any conscious application of physical principles or unique solutions of construction problems. While learned men like Vitruvius and Frontinus did try to lay down some practical principles, the Romans appeared to be quite satisfied with the existing state of affairs.

The book *De architectura* was written by Vitruvius some time between 27 and 17 BC. Book 8 of this treatise is devoted to water. At the end of its preface he stated that:

"As it is the opinion of physiologists, philosophers and priests that all things proceed from water, I thought it necessary as in the preceding seven books [in which] rules are laid down for buildings, to describe in this the method of finding water, [and to mention how] its different properties vary according to the nature of places; how it [the search] ought to be conducted, and in what manner it should

Fig 3 Details of qanāt system (not to scale)



be judged, inasmuch as it is of infinite importance for the purposes of life, for pleasure, and for our daily use."

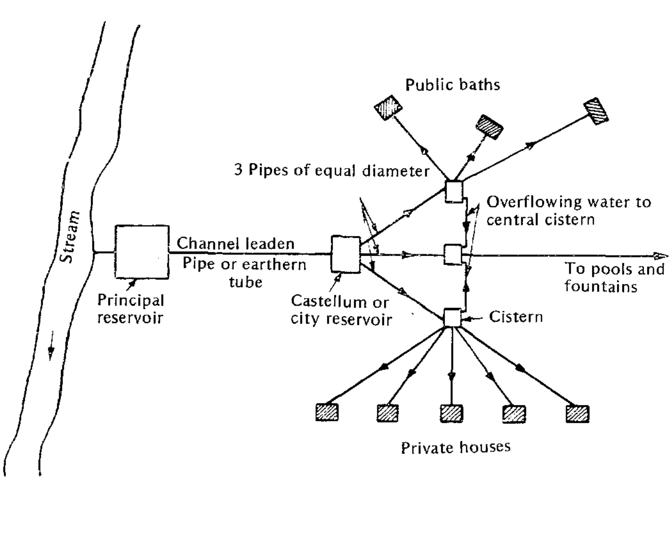
Chapter 1 is devoted to ways of finding water. He suggested that when surface springs are not available, water has to be sought and collected from underground sources, and included tests for locating underground water (for more information, see Biswas 1970).

The final chapter of Book 8 deals with various aspects of water supply systems like aqueducts, pipes, wells, and cisterns. He suggested conducting water by artificial channels or by pipes of lead or baked clay. If a channel was used, it should have a very solid foundation and a minimum slope of 1 in 200. Vitruvius was probably concerned about losses of water by evaporation, and accordingly suggested that channels should be covered.

The artificial, covered channel brought water from the river to a reservoir built within the city walls. From there it was carried by three pipes to three interconnected cisterns as shown in Fig 4. The first cistern would supply water to the baths, the central one to the basins and fountains of the city, and the third to private houses. He suggested that "if water is to be conducted in lead pipes, first build a reservoir at the source; then, let the pipes have an interior area corresponding to the amount of water, and lay these pipes from this reservoir to the reservoir which is inside the city walls. Pipes should be cast in lengths of 3m". He preferred clay pipes to lead ones because it would be comparatively easy to repair damages and because water conducted therein is "not harmful but wholesome".

Much of our detailed knowledge of urban water supply systems of this period comes from the writing of Sextus Julius Frontinus (35?–104 AD). Born in Sicily, he was appointed in 76 AD as the Governor of Britain, one of the important colonies of Rome. Later, in 97 AD, Frontinus was appointed as *curator aquarum* (commissioner of waterworks) by Emperor Nerva.

Fig 4 Water supply system of a Roman city



Frontinus was a versatile man. He wrote seven texts, ranging from surveying to the art of war, and from agriculture to roads. Unfortunately except for his work *De aquis*, the rest are now lost to us. He was about 62 years old when he was appointed water commissioner, and his knowledge of waterworks at that time was very limited. This is clearly stipulated in his masterpiece *De aquis urbis Rome, Libri II*:

"Inasmuch as every office conferred by the Emperor demands especial attention; and inasmuch as I am moved not only to devote diligence, but even love to any matter confided to my care, be it on account of inborn zeal, or by reason of faithfulness in office; and inasmuch as Nerva Augustus, an emperor of whom is difficult to say whether he devotes more love or more diligence to the common weal, has now conferred upon me the duties of water commissioner, duties contributing partly to the convenience, partly to the health, even to the safety of the city, and from olden times exercised by the most distinguished citizens; I therefore consider it to be the first and most important thing to be done, as has always been one of my fundamental principles in other affairs, to learn thoroughly what it is that I have undertaken."

There is no doubt, that Frontinus mastered his new task very quickly.

Aqueducts

The Romans were master builders of *aqueducts* (elevated channels carrying water), not only in their own land but also in many other areas that were under their control. The flow of water was generally by gravity, though inverted siphons were used extensively – especially within city boundaries. Tunnels, if necessary, were also used. The tunnel under Mt. Attliano, built before the time of Frontinus, was nearly 5km long.

For nearly four and a half centuries after the foundation of the city of Rome, the Romans were using water either from the Tiber river or from springs and wells. The city's location, on a group of seven detached hills, with a major river and several streams, was ideal from the water supply standpoint.

The Romans were indebted for their first aqueduct – the Appia – to Appius Claudius Crassus, statesman, financier, and even a poet, who was responsible for building it in 312 BC. Building aqueducts was not a new art, but the present-day ruins of the Roman aqueducts, with their magnificent structures, extensive systems of sluices and gates, long miles of canals, and pretentious outlooks, arouse great admiration among modern engineers. In the fifth century AD, Rutilius Namatianus said: „Why should I mention the aqueducts, sustained upon lofty arches, to which Iris could scarcely lift the waters of the clouds? One might say these were mountains that had grown starward . . . Rivers are intercepted and hidden in thy walls. The lofty baths consume the whole of reservoirs". Later Fabretti described them as *Romanae providentiae magnitudinisque primitiae* (the first fruits of Rome's foresight and greatness).

Frontinus, who was in love with his waterworks, can well be pardoned for his statement: "Will anybody compare the idle Pyramids, or those other useless though much renowned works of the Greeks, with these aqueducts, with these many indispensable structures?".

Details of the aqueducts of Rome as they existed under the jurisdiction of Frontinus are given in Tab 1; and Fig 5 is the famous painting *Wasserleitungen im alten Rom* by Zeno Diemer, in which appear the Anio Novus, the Claudia, the Marcia, the Tepula, and the Julia.

Frontinus, like other Romans, had no clear concept of the fact that discharge in an open channel is dependent on velocity, cross-sectional area, and slope. It was the general practice of the Romans, including Frontinus and Vitruvius, to evaluate discharge by measuring only the cross-sectional area of a stream or by measuring the area of an orifice or a conduit through which the water flowed. (The same error was made by many eminent people later.) It should, however, be pointed out that the equality of the rate of discharge with the cross-sectional area is permissible under certain circumstances.

Their established unit of measurement of flowing water was one *quinaria*. It was the area of a pipe of 1 1/4 *digits* in diameter. Herschel (1899), who translated Frontinus' work, concluded that one quinaria was about 19 to 23 thousand litres per 24 hours, plus or minus 7500 to 11500 litres, according to circumstances, favourable or unfavourable. Frontinus stated that "in setting *ajutages* (a short length of pipe of fixed diameter on which water charges were based), care must be taken to set them on a level, and not place one higher and the other lower down. The lower one will take in more, the higher one will suck in less . . .". If this condition was satisfied, the pipe marked 2 quinariae would then provide twice the discharge of the pipe of 1 quinaria according to the formula $Q = A \cdot 2gh$, assuming that the pipe is discharging into the air and entrance and frictional losses in short lengths are neglected.

The Romans, like the Egyptians before them, were aware that in order to flow, water requires a downward slope. The slopes of the aqueducts were more closely related to the topographical conditions than to hydraulic considerations. The bottom slopes of the same aqueduct frequently varied considerably from about 1 in 2000 to 1 in 250. It is highly unlikely that Roman *mensors*, or *librators*, or *architectons* had any idea of reconciling a particular cross-sectional area with a definite slope in such a manner as to produce a desired discharge. All they seem to have done was to construct a part of the aqueduct, and if the resulting discharge was too little for their liking, they may have either increased the area (less likely) or just increased

Tab 1 Aqueducts under Frontinus' charge (Biswas 1970)

Name	Builder	Date built	Source	Length (km)	Size of aqueduct* (m)	Quality of water	Elevation of delivery above Tiber wharves (ft)	Number of delivery tanks	Amount of water in quinariae*** Available water	Used in city	Used outside the city
Appia	Claudius	312 BC	Spring	16.6	0.6 X 1.8	Excellent	28	20	704	699	5
Anio Vetus	Dentator	272–269 BC	River	63.6	0.8 X 2.1	Turbid	84	35	1610	1102	508
Marcia	Marcius	144–140 BC	Spring	91.3	1.4 X 2.7	Excellent	125	51	1935	1098	837
Tepula	Caepio and Longinus	125 BC	Spring	17.7	0.6 X 1.1	Warmest	128	14	445	331	114
Julia	Agrippa	33 BC	Spring	22.8	0.5 X 1.5	Excellent	133	17	803	597	206
Virgo	Agrippa	19 BC	Spring	20.8	0.7 X 1.5	Excellent	35	18	2504	2304	200
Alsietina	Augustus	10 AD	Lake	32.8	1.8 X 2.7	Not palatable	—	—	392	—	392
Claudia**	Caligula and Claudius	38–52 AD	Spring	69.8	0.9 X 1.9	Excellent	158				
Anio** Novus	Caligula and Claudius	38–52 AD	River	85–158	1.2 X 2.7	Turbid	158	92	5625	3824	1801
				422.77				247	14018	9955	4063

* The size of channels varies from place to place and hence dimensions are only approximate
** The Anio Novus (upper) and the Claudia (lower) form a double-decked aqueduct
*** Quinaria = Roman unit of discharge

the slope (more probable). Thus, in all probability, the slope was fixed by a process of trial and error. Another belief in regard to this subject is that the Romans could have laid out or maintained any desired slope they wanted for their aqueducts with the aid of their favourite type of level, the *chorobate*. The erratic slopes of some reaches in the aqueducts have accordingly been ascribed to a lack of precision of either the chorobates or of the men who operated them (D'Avigdor 1876).

Despite the fact that he did nothing about it, Frontinus did have some vague ideas about the effect of head and velocity on the discharge. He stated:

"Let us not forget in this connection that every stream of water whenever it comes from a higher point and flows into a delivery tank through a short length of pipe, not only comes up to its measure but yields, moreover, a surplus; but whenever it comes from a low point, that is, under a less head, and is conducted a tolerably long distance, it will actually shrink in measure by the resistance of its own conduit; so that on these accounts, either an air or a check is needed for the discharge."

Again later:

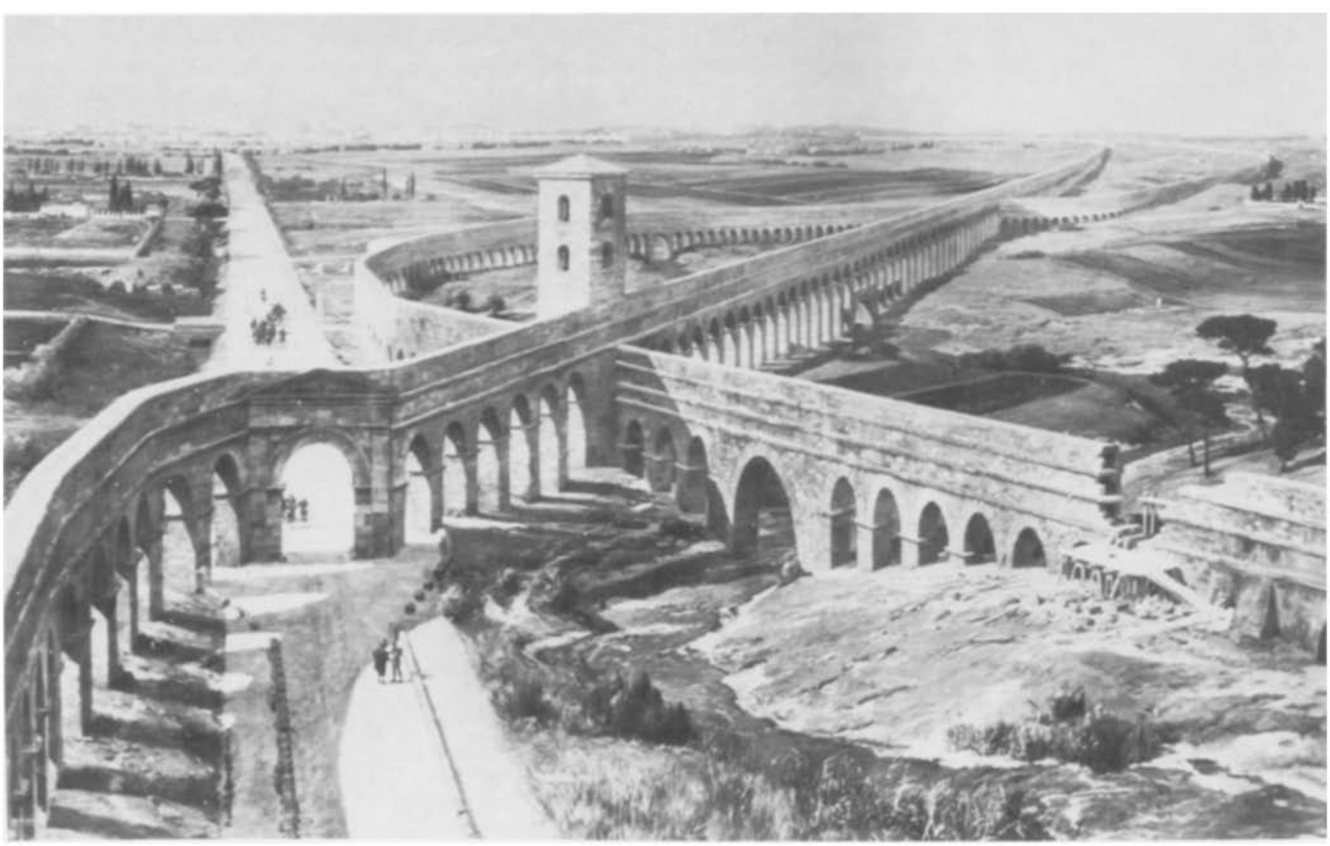
"Whence it appears, that the amount measured by me is none too large; the explanation of this is, that the more impetuous stream of water increases the supply, since it comes from a large rapidly flowing river."

Since these two statements fall into a pattern, Frontinus probably believed that there is normal or standard discharge for a particular cross-sectional area, and if the actual discharge exceeded the standard discharge allocated to the particular area, it is either due to unusual velocity or higher head. But what was the standard discharge for a stream? The incriminating evidence comes from paragraph 65 where he speaks of the Appia aqueduct:

"Appia is credited in the records with 841 quinariae. This aqueduct could not be gauged at the intake, because it there consists of two channels; but at the Twins, which is below Spes Vetus, where it joins the branch of the Augusta, I found a depth of water of 1.5 m, and a width of 0.5 m, making 0.25 m^2 of area, twenty-two 100-pipes [pipes of nominal area of at least 100 square digits] plus one 40-pipe, which makes 1,825 quinariae; more than the records have it by 984 quinariae. It was discharging 704 quinariae; less than credited in the records by 137 quinariae, and, furthermore, less than given by the gauging at the Twins by 1,121 quinariae."

It can be clearly seen from the following calculations that Frontinus took discharge to be equal to the cross-sectional area.

Fig 5 The restored aqueducts of Rome, from a painting by Zeno Diemer, courtesy of Deutsches Museum, Munich (in the left foreground: Anio Novus and Claudia combined in a single structure; on the right: Marcia, Tepula, and Julia also borne by a single arcade)



Area = $1.425\,m \times 0.57\,m = 0.8123\,m^2$

1 quinaria = $4.45\,cm^2$ (area of an orifice 1 1/4 digits in diameter)

$$\text{Discharge} = \frac{8000}{445} = \frac{8123\,cm^2}{4.45\,cm^2} = 1825 \text{ quinariae}$$

The water commissioner was unable to balance his books. That is not surprising because he completely disregarded velocities as well as slopes. However, he did not look far for such discrepancies. The reasons, he asserted, were due to leakages and to fraudulent practices of the Romans who seemed to be experts in tapping water without 'bothering' the authorities. Even allowing for leakage and illegal practices of the Romans, it can be pointed out that the apparent discrepancy was probably due to the velocities which were higher in pipes than in the feeders supplying the aqueduct.

Herschel made a careful study of Frontinus' work, and of the water supply system in use during the corresponding period. He believed that Frontinus' writings reflected the teaching of the Alexandrian school of mathematicians, especially those of Hero of Alexandria. He seems to have assumed that Hero was older than Frontinus. If that assumption was correct (which is debatable), it would indicate that Frontinus obviously failed to grasp the fundamental law of flow in open channels or conduits as had been advocated by his teacher. It is evident that Frontinus' concept of the measurement of discharge was the one that prevailed during the Roman civilization. The lone exception during this period was Hero of Alexandria, who perhaps correctly understood the principle, but unfortunately had been unheeded (Biswas 1970).

Frontinus was clearly concerned with water quality. He discussed purity, turbidity, and palatableness of water, and suggested that the various uses of water should be consistent with quality:

"...... Marcia should serve wholly for drinking purposes", (since its water is "charming in its purity and coldness") "and that the others should be used for purposes adapted to their special qualities. For example, it was ordered for several reasons, that Old Anio should be used for watering the gardens, and for more dirty uses of the city ......"

The quality of water in the various Roman aqueducts are indicated in Tab 1.

Frontinus was also aware of maintaining the quality of water. He enacted a law which categorically stated "no one shall with malice pollute the waters where they issue publicly. Should any one pollute them, his fine shall be ten thousand *sestertii*". According to Herschel (1899), the fine imposed at that time amounted to about $292 of coins, which undoubtedly was substantial sum.

Conclusion

It is clear that the urban water supply system was well developed by the time of the Roman Civilization. Most of our knowledge of water supply systems of this period comes from Frontinus. Though not familiar with water supply systems when he was initially appointed as the *curator aquarum*, he made a determined attempt to find out the state of knowledge prevailing at that time – by collecting "all that I could gather as bearing on the subject matter". He systematically organized and codified the knowledge. The results of his analysis and synthesis served, as he had originally intended, for his "own instruction and as a guide" and for the benefit of his successors. Equally, it has also become a primary source of information on the technology and practice of urban water supply systems prevailing at that time.

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