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The Roman Civilization

INTRODUCTION

The expression Roman Civilization, as used in the present chapter, refers to that period which extended from about 100 B.C. to the end of the second century A.D. Perhaps it should have been called the Greco-Roman Civilization, because the Romans had relatively very few new independent conceptions to offer even though they managed to build magnificent aqueducts to supply Rome with millions of gallons of water daily, remarkable sewer systems, and a very fine harbour. Even during the peak of the Roman Civilization, the language of learned men was Greek, and all the major writers of the time (like Varro, Vitruvius, Celsus, Pliny, and Seneca) preferred to demonstrate an encyclopaedic knowledge rather than to express original and independent thoughts. This had a profound effect on the intellectual life in Western Europe throughout the early Middle Ages.

It can be said, with some justification, that the Romans were 'practical' engineers – for example, their awe-inspiring aqueducts were built without any conscious application of physical principles or unique solutions of constructional problems. Men like Vitruvius and Frontinus did try to lay down some practical principles, but as far as the Romans were concerned, they were satisfied with the existing state of affairs.

VITRUVIUS

His life

Vitruvius was born in northern Italy, possibly at Verona, and except for what can be learned about his life from his famous treatise *De architectura libri decem*, he is practically unknown. His book was dedicated without further identification to the 'imperator Caesar'. Probably the emperor in question was Octavianus, the adopted son of Julius Caesar.[1] It is generally agreed that *De architectura* was written sometime between 27 and 17 B.C.[2] Since he describes himself as an old man in his book, it can be inferred that he was at his prime during the second half of the first century B.C. Some have claimed that the book was written around 400 A. D. by a sort of 'pseudo-Vitruvius',[3] who was an ordinary compiler with neither the intelligence to interpret his source nor the literary skill to express himself. It must be pointed out, however, this is a very minority and rather ludicrous opinion.

The book, written in Latin even though the prevalent learned language of the time was Greek, is a diffused compilation on architecture, and Vitruvius was most certainly not a lover of Muses. It dwelt heavily on the Hellenistic tradition rather than the Roman and had a profound effect on the classical architecture, even as late as the Renaissance. Vitruvius had a multi-disciplinary approach to that subject, and advocated that it be combined with knowledge of astronomy, drawing, geometry, history, law, medicine, music, optics, and philosophy. He himself seems to have been a rather unsuccessful architect but he expressed a high regard for himself in the book: 'I promise and expect that in these volumes I shall undoubtedly show myself of very considerable importance not only to builders but also to scholars'.[4] His ambition was undoubtedly more than fulfilled as almost all the earlier theories and practices of renaissance pseudoclassical architecture were based on it. Celebrated architects like Bramante, Michelangelo, and Vignola were considerably influenced by that treatise.

How to find water

Book 8 of his 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 be judged, inasmuch as it is of infinite importance for the purposes of life, for pleasure, and for our daily use.'[5]

Chapter 1 is devoted to ways of finding water. When surface springs are not available, water has to be sought and collected from underground sources. The test suggested for locating underground water is to lie flat on the ground before sunrise (figure 1) in the area where water is to be sought, and with one's chin on the ground, to take a close look at the country side, the reason being that the search will then be limited approximately to the same level on the ground. Water can be expected to be found in places where vapours arise from the earth (an impossible condition if the soils were dry). Water may also be sought in localities where there are plants of a type which generally grow in marshy areas. When a promising location is found a hole, not less than three feet square and five feet deep, is to be dug and, a bronze or lead vessel with its inside smeared with oil, is to be placed upside down in that hole at about the time of sunset. The hole is then to be filled with rushes or leaves and earth. If drops of water are found within the vessel on the subsequent day, water should be found at that location. It should be pointed out that nowhere in his book does Vitruvius advocate using a divining red. In fact, all of his methods for locating underground sources of water have rational bases.

Soil types also provide some idea about the presence of ground water, and hence the nature of ground should be studied carefully. Details regarding the availability of water in various types of soils (according to Vitruvius) are shown in table 1.

Figure 1. Vitruvius' method for locating water.

TABLE 1
Details of water available in various types of soils

Type of soil	Depth at which water may be available	Amount	Taste	Remarks
Clay	Near the surface	Scanty	Not good	--
Loose gravel	Lower down the surface	Scanty	Unpleasant	Muddy
Black earth	--	--	Excellent	Available after winter rains
Gravel	--	Small and uncertain	Unusually sweet	--
Coarse gravel, common sand and red sand	--	More certain	Good	--
Red rock	--	Copious	Good	Difficult to obtain due to percolation
Flinty rock and foot of mountains	--	Copious	Cold and wholesome	--

A well is to be sunk when a site is located where the experiments mentioned above indicate the possibility of existence of water. Several additional wells are then sunk around the original well and by a series of underground channels water must be brought into a single place from which it can be carried to other locations as needed. Vitruvius suggested that water can be best sought in mountainous regions because water found there will be sweet, whole some, and abundant. There is also no loss of water in such regions due to evaporation as they are 'turned away from the sun's course' and the presence of a forest makes it impossible for the sun's rays to reach the surface water.

The hydrologic cycle

Vitruvius was familiar with the meteorological writings of Aristotle and Theophrastus, and he had a reasonably clear concept of the hydrologic cycle. He said that valleys between mountains are subjected to much rainfall, and snow remains on the ground there much longer because of the dense forests. When the snow melts, it percolates through the interstices of the earth and finally reaches the lowest spurs of the mountains 'from which product the stream flows and bursts forth'.

Vitruvius, like Hippocrates and Aristotle, believed that only the thinnest, the lightest, and the most subtly wholesome part of water was evaporated, and that the heaviest, the harsh, and the unpleasant parts were left behind. The moisture arising from the earth, during the sunrise, drives the air before it, and in turn receives impetus from the air which rushes in behind it. That onrushing air drives the vapour in every direction – thus creating gales, blasts, and eddies of wind. As the wind travels, it collects further moisture from springs, rivers, marshes, and the sea because of evaporation due to the sun's heat. The 'condensed vapour' then rises to form clouds. Clouds are supported on a 'wave of air', and precipitation occurs when they hit mountains because of the shock sustained and because of their fullness and weight. That explains why there is always more rainfall near mountains than near plains. The rise of vapours, moisture, and clouds from the earth, therefore, is seemingly dependent on the earth's retention of intense heat, great winds, coldness, and on the presence of large amounts of' water. 'Thus when, from the coolness of the night, assisted by the darkness, winds arise, and clouds are formed from damp places, the sun, at its rising, striking on the earth with great power, and thereby heating the air, raises vapours and dew at the same time.'[6]

The process is comparable to that of a hot bath where water being heated vapourizes, and the rising vapour forms droplets on the ceiling. When the droplets become large enough they fall on the head of bathers. It is reasonable to assume that since there is no source of water on the ceiling, the water must have come from the bath. The various concepts of Vitruvius were later copied and recopied, and the analogy of the bath house has been repeated as late as the tenth century A.D.

The reasons ascribed by Vitruvius for the origin of hot and cold springs were somewhat analogous to the ones postulated later by Kircher[7] during the seventeenth century. The Roman architect believed that fires are somehow kindled in alum, asphalt, or sulphur in the earth, and that they heat the soil above them. If it so happens that there is a spring in the upper stratum, the water gets heated and produces a hot spring. If the stream travels a long distance after passing through the heated region, the water cools off by the time it reaches the surface, but its taste, smell and colour becomes spoiled in the process.

The final chapter deals with aqueducts, pipes, wells, and cisterns. The methods he suggested for conducting water were by artificial channels or within 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 brings water from the river to a reservoir built within the city walls. From there it is to be carried within three pipes to three interconnected tanks (figure 2). The first tank should supply water to the baths, the central one to the basins and fountains of the city, and the third to private houses. 'If the 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 ten feet.' 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'.

Vitruvius, like other Romans, seemed totally unaware of the fact that discharge depended on both the velocity and cross-sectional area of a stream. (Hero of Alexandria was perhaps the only contemporary Roman who had a clearer conception of that phenomenon.) It was the general practice of the Romans, including 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. Vitruvius also erred about the source of the Nile. His contemporary, Juba II (d. 20 A.D.), the King of Mauretania, stated in his work *Libyca* that the source of the Nile was in Western Mauretania,[8] and probably Vitruvius was aware of his work. The Nile was a constant wonder to the people of the ancient civilizations and they kept speculating time and again about its origin and the regularity of its inundation.[8]

In the first century A.D., the Roman polymath Pliny quoted Vitruvius extensively, although nowhere did he acknowledge the source of that information.

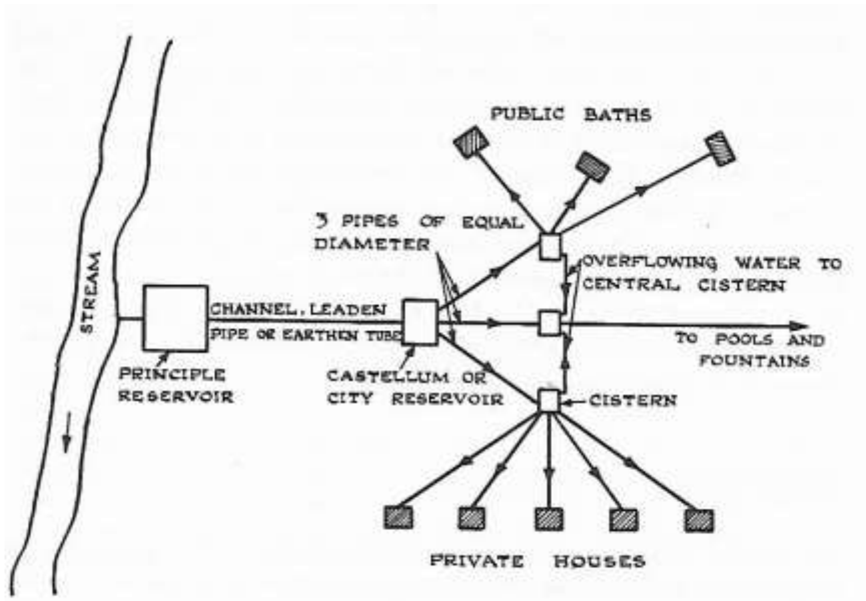

Figure 2. Water supply system of a Roman city.

MEASUREMENT OF DISCHARGE

Of all the varieties of hydrologic data, stream flow records are probably of the greatest importance to hydrologists. However, the present-day simple concept that discharge is equal to the cross-sectional area times the velocity ($Q = A \times V$), which is almost the first lesson in elementary hydraulics, took a long time to make a permanent appearance. It was first enunciated by Hero of Alexandria but it seems to have attracted very little attention at that time. The principle was never used until 1628, when it was derived independently by Benedetto Castelli.* Considerable controversy exists amongst the historians of science over the time in which Hero of Alexandria lived. The time varies from about 150 B.C. to 250 A.D.; but the present consensus[9] seems to be that Hero flourished sometime after 65 A.D. but before 150 A.D. If this is correct, Hero was post-Vitruvian and almost a contemporary of the Roman water commissioner Sextus Julius Frontinus. Two of the most important works of Hero, chief of the Alexandrian School, are *Pneumatica and Dioptra.* Like Thales, he was a practical man, and was mainly concerned with the practical applications of knowledge. Consequently it is no surprise to find that he has been sometimes called ‘the first engineer’.[10]

In Pneumatica Hero describes more than 20 methods of application of syphon, and explained its use for both drainage and irrigation. According to him, syphons were extensively used for

*Leonardo da Vinci made studies of the distribution of velocities in open channels, but the author has found no evidence yet that he actually computed any discharge values from such data.

irrigating lands bordering the desert, and could be successfully used for conveying water over across long hills and valleys.

The second book *Dioptra* was translated by Pappus in the third century A.D. It is a remarkable book on land surveying, and is so called because of the instrument describes in it which could be used for similar purposes as the modern-day theodolite. From the standpoint of hydrology, the most important contribution of Hero is his method of determining the discharge of a spring. The problem and the solution as given by him is as follows:

'Given a spring, to determine its flow, that is, the quantity of water which it delivers.
One must, however, note that the flow does not always remain the same. Thus, when there are rains the flow is increased, for the water on the hills being in excess is more violently squeezed out. But in times of dryness the flow subsides because no additional supply of water comes to the spring. In the case of the best springs, however, the amount of flow does not contract very much.
Now it is necessary to block in all the water of the spring so that none of it runs off at any point, and to construct a lead pipe of rectangular cross-section. Care should be taken to make the dimensions of the pipe considerable greater than those of the stream of water. The pipe should then be inserted at a place such that the water in the spring will flow out through it. That is, the pipe should be placed at a point below the spring so that it will receive the entire flow of water. Such a place below the spring will be determined by means of the dioptra.
Now the water that flows through the pipe will cover a portion of the cross-section of the pipe at its mouth. Let this portion be, for example, 2 digits* [in height]. Now suppose that the width of the opening of the pipe is 6 digits, 6 x 2 = 12. Thus the flow of the spring is 12 [square] digits.
It is to be noted that in order to know how much water the spring supplies it does not suffice to find the area of the cross-section of the flow which in this case we say is 12 square digits. It is necessary also to find the speed of flow, for the swifter is the flow, the more water the spring supplies, and the slower it is, the less. One should therefore dig a reservoir under the stream and note with the help of a sundial how much water flows into the reservoir in a given time, and thus calculate how much will flow in a day [figure 31]. It is therefore unnecessary to measure the area of the cross-section of the stream. For the amount of water delivered will be clear from the measure of the time.'[12]

The concept that stream discharge is dependent on velocity, as suggested by Hero, was an isolated instance, and was not accepted probably because he was much ahead of his time. As previously indicated, two great men of that period, Vitruvius and Frontinus, considered that the discharge amounted to the cross-sectional area of the stream, and theirs was the accepted practice as of that time. Since Vitruvius' concept has already been discussed, only Frontinus' approach will next be briefly described.

Sextus Julius Frontinus (35?–104 A.D.), one time Governor of Britain under Emperor Vespasian, received his appointment as commissioner of water works *(curator aquarum)* of Rome from Emperor Nerva in about 97 A.D. Though he was about sixty-two years old when he accepted this new job, he had a great love for the work. He probably began writing his masterpiece *De aquis*

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*The digit is an ancient Greek unit of length called *dactylos* and is equal to 1.85 cm[11] *urbis Romae, libri* II during the year that followed.[13] The book contains a wealth of information on water supply systems and methods used by the Romans during the first century A.D.

Figure 3. The first correct measurement of stream flow by Hero of Alexandria (reconstructed by Arthur H. Frazier).

Herschel made a careful study of Frontinus' work, and of the water supply systems in use during the corresponding period. He believed that Frontinus' writings reflected the teachings of the Alexandrian school of mathematicians, especially those of Hero of Alexandria.[14] He seems to have assumed that Hero was at least older than the Roman water commissioner. 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.

As has been explained, Frontinus had no clear concept of the fact that discharge in an open channel is dependent on velocity, cross-sectional area and slope. 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 the slope (more probable). Thus, in all probability, the slope was fixed by a process of trial and error. Another belief in regard to his 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.[15]

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, in paragraph 35, that:

'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 in paragraph 13 he said:

'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 and rapidly flowing river.'

Since these two statements fall into a pattern, Frontinus probably believed that there is a *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 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 5 feet, and a width of one foot plus ¾, making 8¾, square feet of area, twenty-two 100-pipes [pipes of nominal area of at least 100 square digits] plus one 40-pipe, which makes 1825 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 1121 quinariae.'

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

Area = 5 x 1.75 = 8.75 sq. ft
= 1260 sq. in
1 *quinaria* = 0.69026 sq. in. (area of an orifice 1¼ digits in diameter)

$$\text{Discharge} = \frac{1260}{0.69} = 1825 \textit{ quinariae}$$

The water commissioner was unable to balance his books, and it 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 because the velocities in pipes were higher than in the feeders supplying the aqueduct.

Their established unit of measurement of flowing water was one *quinaria*. It was the area of a pipe of 1¼, *digits* in diameter. Herschel from his studies concluded that one *quinaria* was about '5000 or 6000 U.S. gallons per twenty-four hours, plus or minus 2000 or 3000 U.S. gallons, according to circumstances, favourable or unfavourable'.[16] It should, however, be pointed out that the equality of the rate of discharge with the cross-sectional area is permissible under certain circumstances. 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 the 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 $Q = A \sqrt{2gh}$, assuming that the pipe is discharging into the air, and entrance and frictional losses in short lengths are neglected. It is firmly believed that the concept of Frontinus for the measurement of discharge was the one that prevailed during the period of the Roman Civilization. The lone exception was that explained by Hero, whose correct understanding of the phenomenon unfortunately had gone unheeded.

AQUEDUCTS OF ROME

For nearly four and a half centuries after the foundation of the city, the Romans were using water either from the Tiber, or from wells and springs. They were indebted for their first aqueduct[17] to Appius Claudius Crassus, statesman, financier, and even a poet, who was responsible for building the Appia in 312 B.C. Building aqueducts was not a new art, as will become evident from a reading of chapter 1, but just 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.[18] In the fifth century A.D., 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 star-ward ... Rivers are intercepted and hidden in thy walls. The lofty baths consume the whole of reservoirs'. Later Fabretti describes them as *Romanae providentiae magnitudinis que 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[19] as they existed while under the jurisdiction of Frontinus are given in table 2, and figure 4 is the famous painting *Wasserleitungen in altem Rom* by Zeno Diemer in which appear the Anio Novus, the Claudia, the Marcia, the Tepula, and the Julia.

Figure 4. The aqueducts of Rome, restored. The Anio Novus and the Claudia in the left foreground, combined in a single structure; the Marcia, Tepula, and Julia also borne by one single arcade, on the right (painting by Zeno Diemer, by courtesy of Deutsches Museum, Munich).

CONTRIBUTION OF SENECA

Lucius Annaeous Seneca (4 B.C.–65 A.D.), a Spaniard (figure 5) was brought to Rome by his father at an early age. He had the unenviable distinction of being associated with Caligula the madman (37–41 A.D.), Claudius the imbecile (41–54 A.D.), and Nero the monster (54–68 A.D.). He paid the penalty for having lived in such troubled times by being ordered to prepare for death by his former pupil Nero, who gallantly allowed him a choice of various means with which to perform the enforced suicide. The Stoic is best known for his moralistic writings and tragedies, but to hydrologists his work *Quaestiones naturales* written soon after 63 A.D.,[20] is of major interest. That work consists of seven books which deal with astronomy, physics, physical geography, and meteorology. He draws heavily on Greek sources[21] – mainly Aristotle, Theophrastus, Posidonius, and Asclepiodotus. Unfortunately the meteorological writings of Posidonius and Asclepiodotus are no longer extant and only about four pages of an abstract of Theophrastus' work made by an unknown Arab has survived.[22] There is a great gap in the development of science from Aristotle and Theophrastus to Seneca but there is even a greater gap between Seneca and the beginning of the Renaissance.

Figure 5. Bronze head of Lucius Annaeus Seneca from Herculaneum (by courtesy of National Museum, Naples).

In Book IV of *Quaestiones naturales* Seneca discusses hail and snow in a rather frivolous manner, He said that he would be rather audacious if he suggested hail is formed in the sky exactly in the same way as ice on the earth, except in the previous case the whole cloud is frozen.[23] He then decided to imitate the chroniclers who, after lying to their heart's content, refuse to take responsibility for any particular statement and refer to the authorities for its authenticity. Hence, if his friends doubt his words about the formation of snow and hail, they can refer back to Posidonius who would vouch for it as if he had witnessed the whole process himself. Hail is formed from a rain-cloud which has just turned into liquid. It has a round shape because drops of all kinds tend to be globular, and even if it started its descent in an irregular shape, its sides would get rounded as it falls whirling through thick air. Snow, on the contrary, is not spherically shaped because it is not so solid and it does not fall from as great a height. Hail is simply ice suspended in mid-air, and similarly snow is suspended hoar-frost. He finishes his dissertation in a light vein, and then proceeds to inquire into the distribution of density and temperature in the atmosphere.

Seneca's views on the origin of rivers and springs will be discussed in the next subsection along with those held by some others of his period, and a discussion of his writings on the causes of the rise of the Nile will appear in chapter 6.

TABLE 2

Aqueducts under Frontinus' charge

Name	Builder	Date build	Source	Length (miles)	Size of* aqueduct (ft)	Quality of water	Elevation of delivery above Tiber wharves (ft)	Number of delivery tanks	Amount in quinariae		
									Available water	Used in city	Used outside the city
Appia	Claudius	312 B.C.	Spring	10.29	2.0 x 6.0	Excellent	28	20	704	699	5
Anio Vetus	Dentator	272–269 B.C.	River	39.55	2.5 x 7.0	Turbid	84	35	1610	1102	508
Marcia	Marcius	144–140 B.C.	Spring	56.73	4.6 x 9.0	Excellent	125	51	1935	1098	837
Tepula	Caepio and Longinus	125 B. C.	Spring	11.00	2.0 x 3.5	Warmest	128	14	445	331	114
Julia	Agrippa	33 B.C.	Spring	14.19	1.5 x 5.0	Excellent	133	17	803	597	206
Virgo	Agrippa	19 B.C.	Spring	12.97	2.2 x 5.0	Excellent	35	18	2504	2304	200
Alsietina	Augustus	10 A.D.	Lake	20.39	5.8 x 8.7	Not palatable	--	--	392	--	392
Claudia**	Caligula and Claudius	38–52 A.D.	Spring	43.34	3.0 x 6.2	Excellent	158	92	5625	3824	1801
Anio** Novus	Caligula and Claudius	38–52 A.D.	River	53.98	4.3 x 9.0	Turbid	158				
				262.44				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.

THE HYDROLOGIC CYCLE

The Latin poet and philosopher Lucretius Carus Titus (earlier half of the last century B.C., possibly 96?–55 B.C.) left a work *De rerum natura* (On the nature of things). It is his only work that is known to still exist.[24] He believed that moisture rises from everything, especially from the sea. When headlong winds drive the 'clouds' across a deep sea, the clouds pick up an abundant supply of moisture just like a woolen fleece soaks up dew. Then the upraised vapours assemble in a thousand ways only to lose their water content for either of these two reasons:

'The power of wind drives it [densely packed clouds] along.
The very multitude of clouds collected in a great array
And pushing from above,
Makes rains stream out in copious shower.
Then too,
When clouds are scattered by the winds or broken up,
Smitten above by rays of sun,
They send their moisture out and drip
As lighted tapers held above a scorching fire Drip fast.'[25]

This process constitutes only one-half of the hydrologic cycle. The other half is discussed in connection with the sea[26] which remains constant in size despite the large quantity of water being constantly added to it by rivers, springs, torrential rains, as well as by subterranean streams. Compared to the vastness of the sea, however, all the extra water coming in is hardly equal to a single drop. Besides, the sea loses a considerable amount of water due to evaporation from both the heat of the sun and winds sweeping the surface of the sea, and, as already explained, 'clouds' pick up much moisture. Since the earth is porous much water is lost from the sea by leakage, and, then:

'The brine is filtered off, the moisture trickles back
Assembles at the source of every stream
Thence flows through earth in torrent fresh
Wherever once a way is cut
To let the waters run in liquid march.'[26]

Thus Lucretius believed that rivers do not originate from precipitation but from the filtration of sea-water which is lost due to seepage. His concept on the origin and rise of the Nile[8] will be discussed in chapter 6.

From the presently available written works of antiquity, Vitruvius may be credited with the first pluvial explanation of the hydrologic cycle although, as discussed in the previous chapter, he probably got the idea from Greek sources – from either Theophrastus or Posidonius or from both of them.

Book III of Seneca's *Quaestiones naturales* is devoted to various forms of water but mainly to both surface and subterranean springs and rivers. He classifies water into two main categories: standing, as in lakes, and running, as in rivers and springs. Water is stagnant if it lies on a horizontal plane, and it is running if it exists on sloping ground. But why does not the sea grow larger from the water it continually receives from the rivers? And, as a matter of fact, why does not the earth run out of water from this continual loss? Seneca was ready with the answers but before presenting them he first stated the opinions expressed by some learned men. He refers to Lucretius' concept, but as it is not good enough to even be commented upon, he moves on to another one, namely that water in a river originally comes from precipitation. The philosopher strongly opposed that concept. As a diligent digger among his vines, he confidently asserted that even the heaviest rainfall could not percolate to a depth of more than 10 ft below the surface. When the ground was dry, all water is absorbed by the upper layer, and nothing reaches the lower one; and when it is saturated, the rain-water would find its way into river channels. River levels do not rise with first rainfall because the thirsty ground absorbs it all.

Next, he inquires, how can rivers originate from rocks and mountains? Rainfall has to flow off the bare crags because there is no earth to infiltrate. This surely must be an unanswerable question. In fact it is, but if the stoic had been observant enough, he would have failed to find a single spring issuing from any summit without its having any appreciable gathering grounds. Finally, as rainfall cannot infiltrate to more than 10 ft below the surface, how can one explain the existence of rich springs of water at a depth of 200 to 300 ft in the driest of localities?

Having refuted the two main theories basic to the hydrologic cycle, he gave his own thoughts on the subject which, as can be seen from the following discussion, were undoubtedly coloured by Aristotle's teachings. Three reasons were suggested for the origin of underground water. They are:

(i) earth itself contains moisture which is forced out at the surface;
(ii) air within the earth is being continually converted into water by the underground forces of perpetual darkness, everlasting cold and inert density; and
(iii) the doctrine of interconvertibility of elements, i.e., earth within its interior turns itself into water.

If one is surprised at the large and continuous supply of fresh water in rivers, he has only to look at the size of reservoirs from where it came:

'Surely you might as well be surprised, when the winds drive hither and thither the whole atmosphere, that the supply of air does not fail, but flows on day and night increasingly. And the wind, remember, is not confined to a definite channel, as rivers are, but goes with wide sweep over the broad expanse of heaven. You might well, too, be surprised that after so many breakers have spent their force, any succeeding wave is left.'[27]

If one still asks how water is produced, he is met with a similar question: how air or earth is produced. There are four elements in nature, and one is not entitled to ask where water came from; it is just one of the four parts of nature.

Having settled the question, Seneca produced to explain why water in certain water courses stops flowing at times. The reason is simple as the channels are cut off by rocks or earth displaced by earthquake.[28] He believed that the earth contains not only veins of water but also subterranean rivers, huge lakes, and a hidden sea from all of which the rivers at the surface obtain their supplies of water.[28] Finally, everyone knows that there are some standing waters which have no bottoms, and this water is the perpetual source of large rivers.

Seneca's discussion of the origin of the Nile will be treated with the others in chapter 6.

One of the greatest legacies of Roman times preserved from antiquity is the *Natural history* of Pliny the Elder (Gaius Plinius Secundus, 23–79 A.D.). He was a prolific writer who had an indefatigable curiosity about natural phenomena. He met his death while recording an eruption of Mount Vesuvius, a martyr to scientific curiosity. It is to be noted that the writings of Lucretius, Seneca and Pliny on meteorological subjects have marked resemblances and dissimilarities which probably indicate that they were drawing their materials from the same primary sources.[29]

Pliny was confident that the freezing of rain is the cause of both hail and snow; hail occurs when it is frozen hard, snow occurs when it is less firmly concreted. Similarly, hoar-frost is frozen dew. As to the origin of springs and rivers, he said:

> 'The earth opens her harbours, while the water pervades the whole earth, within, without and above; its veins running in all directions, like connecting links, and bursting out on even the highest ridges; where, forced up by air, and pressed out by the weight of the earth, it shoots forth as from a pipe …'[30]

RAINFALL MEASUREMENTS AT PALESTINE

After Kautilya, the next mention of rainfall measurement appears in a Palestinian book of religious writings called the *Mishnah.* The book records nearly 400 years of Jewish cultural and religious activities in Palestine, from sometime around the earlier half of the second century B.C. to the close of the second century A.D.[31] In a doctoral dissertation, Vogelstein[32] has pointed out that rain gauges were used in Palestine during the time of the *Mishnah.*[33–36] Rainfall was recorded during an entire year, and the total time was divided into three periods:

> 'First, that of the early rain, which moistens the land and fits it for the reception of the seed, and is consequently the signal for the commencement of ploughing. Second, the copious winter rain, which saturates the earth, fills the cisterns and pools, and replenishes the springs. Third, the latter or spring rain, which causes the ears of corn to enlarge, enables the wheat and barley to support the dry heat of the early summer, and without which the harvest fails … As a rule, it may be considered that the

autumn or early rains extend from the commencement of the rainy season in October or November until the middle of December, the winter rains from the middle of December until the middle or end of March, and the latter or spring rains from the middle of March until the termination of the rainy season in April or May.'[37]

The rainfall values recorded for corresponding periods were as follows:

Early rain period	1 *tefah* (about 9 cm)
Second period	2 *tefahs*
Third period	3 *tefahs*
Annual rainfall	6 *tefahs* = 54 cm.

It is not possible to find out if the results were isolated readings for one year or averages for a number of years. It was also said that rainfall percolated to a depth of 1 *tefah* in barren soils, 2 *tefahs in* medium soil, and 3 *tefahs* in broken up arable lands. Obviously like the Indian practice, measurements of rainfall in Palestine were initiated primarily because of its importance to agriculture. Generally benedictions were said at the beginning of the rain period as well as alter a certain amount of rain had fallen (when a container having a volume of 0.137 litre had been filled).[32]

It is rather interesting to note the amount of rainfall then considered as normal for a good harvest corresponds quite closely with the observations made by Thomas Chaplin at Jerusalem during the late nineteenth century.[38]

CONCLUSION

The major development during the Roman Civilization, so far as the science of hydrology is concerned, was undoubtedly the concept of Hero of the measurement of discharge, but because Hero was far ahead of his time, it is no surprise that his idea attracted scant attention. Both Vitruvius and Frontinus believed that discharge of a natural stream or discharge through a pipe is equal to its cross-sectional area, irrespective of its velocity. It took another seventeen centuries for the father and son team of john and Daniel Bernoulli to separately publish in 1738, their different mathematical demonstrations of the elementary principle of flow; $v = \sqrt{2gh}$. The Romans were aware that area of a pipe is equivalent to ¼ D^2 but they seem to have had no concept of cubic measures, and units of discharge, like cubic feet per second, were perhaps beyond their wildest imagination.

Romans were practical people. While reading *De aquis* one gets the impression that Frontinus realized that something was wrong with his concept of equating area with discharge. Thus he speaks vaguely of the effects of velocity, head of water, boundary resistance, and frictional loss without having clear conception of any of these phenomena. The Romans built great water works and quite justifiably they were proud of them. It is concluded that they were built by purely empirical methods, without much understanding of physical principles, but it should be emphasized that they did work and served their purposes admirable.

So far as the concept of the origin of rivers and springs is concerned, it was stated reasonably well by Vitruvius. It is highly likely that the pluvial concept was first given by Theophrastus, but in the absence of any authentic records it will always remain a purely conjectural assumption.

Finally, the quantitative measurement of precipitation by the Jews of Palestine for agricultural purposes was an important development. There seems to be no connection between the Indian practice of the fourth century B.C. and the Palestinian development of the first century A.D. Both were independent and isolated practices and did not continue for a, long time.

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