Building Services Engineering

A Review of Its Development

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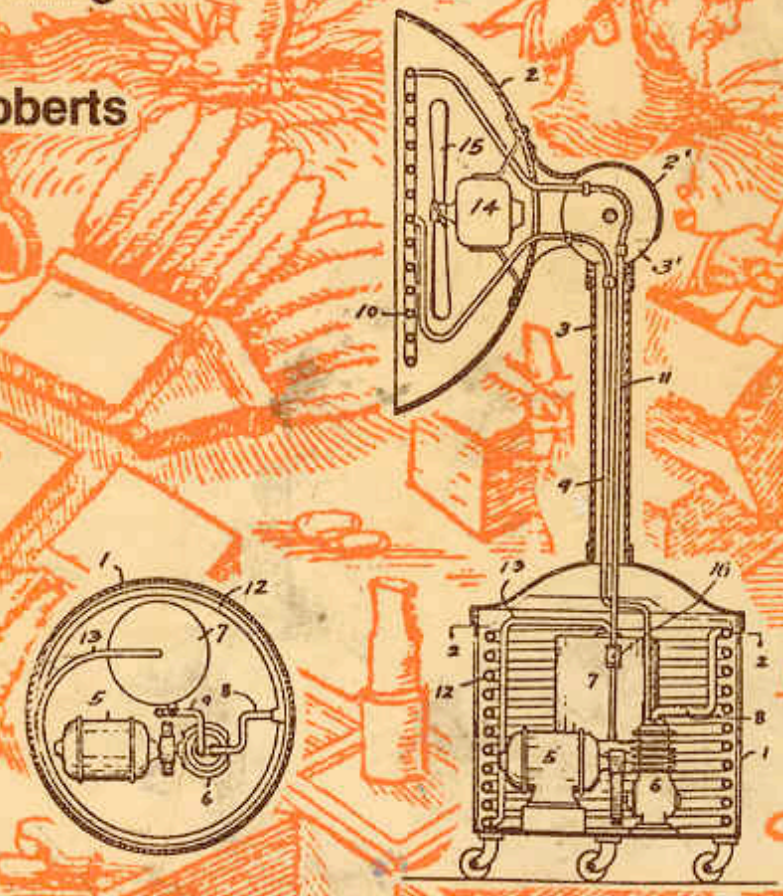

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Chapter 7

PLUMBING AND SANITATION

7.1 WATER SUPPLY

7.1.1 Early storage and distribution methods

The earliest water supplies were obtained from springs and rivers, surface water, shallow wells and dew-ponds. The first major developments were in the use of water for irrigation, and these are still the most important use in some areas. Organised irrigation is at least six thousand years old, dating from the New Stone Age. A change of climate, with less rainfall, in the Mediterranean and Near East forced the peoples to move into the river valleys, which had to be drained and cleared. Digging of drainage and irrigation channels could be achieved only by co-operative effort and team-work — a powerful force towards the formation of nations and a central power. This was an important advance in civilisation.

One of the oldest cities which has been excavated is Jericho, where digging in the 1950's uncovered enormous walls and ditches which modern dating techniques have placed as being constructed around 8000 B.C. Archaeologists examining these early constructions found large walls which had no opening except a top channel about 0.5 m deep, the channels being full of silt which implies running water. Running water at this height, since some of the walls were probably more than 4.5 m high, suggests aqueducts; possibly for purposes of irrigation, or possibly for sanitation.(5) If this assumption is correct Jericho had a planned water distribution system in daily use 5000 years before the building of Egypt's pyramids.

The earliest reservoir is probably that recorded at Babylon in about 4000 B.C. The Hanging Gardens (Fig. 7.1) were irrigated by means of a screw drawing water from the river.

The ancient empires of the Near East (3200-600 B.C.), in Egypt, Mesopotamia and the Indus valley, were urban civilisations. The principal invention of this period was the aqueduct* — originally the Persian *qanat*.(26) The Shatt-el-Hai was built to convey the waters of the high-level Tigris over the plains to Ur. This system fell to ruin in the 13th century when the Mongols overran the region. The invention of the aqueduct meant that settlements no longer had to be situated by a river or other

*The aqueduct was then any channel, tunnel or bridge for carrying water, and not, as now, a bridge only.

source of water: the site could be chosen for other, perhaps more cogent, reasons. The Greeks, Romans and Palestinians all brought water to cities over long distances by these means. The Greek, Eupalinus of Megara, constructed an aqueduct on Samos in 600 B.C. and this included a tunnel 2.4 m in diameter and nearly 1.6 km long.[3] The Assyrian aqueduct to supply Nineveh, built by Sennacherib in 691 B.C., included a 300-m bridge over a valley and elaborate water conduits:

> "of a size never before equalled: eighteen canals carried water from 48 km away, and the entire system of graded reservoirs and aqueducts contained more than two million blocks of stone."[15]

An elaborate monolithic basalt water tank of this period still survives.

The supply to Pergamum was led from the mountains through a system of pipes over hills and valleys into the plains. The maximum pressure in the main was some 2 MPa. Knossos in Crete had a piped water supply, for which pottery pipes ¾ m long, and tapering from 150 to 100 mm were used (*ca.* 2000 B.C.). Pottery pipes in the Canaanite city of Hazor from about 1300 B.C. were 1 m long: they were elliptical in shape and could be fitted together. Branch pipes could be fitted into holes in the side of the main pipe. Socketed pipes were in use in Greece. By Roman times, parallel-sided pipes with well-formed sockets were common, examples having been found at Verulamium, Lincoln and Rome. They were joined with quicklime and oil.[25]

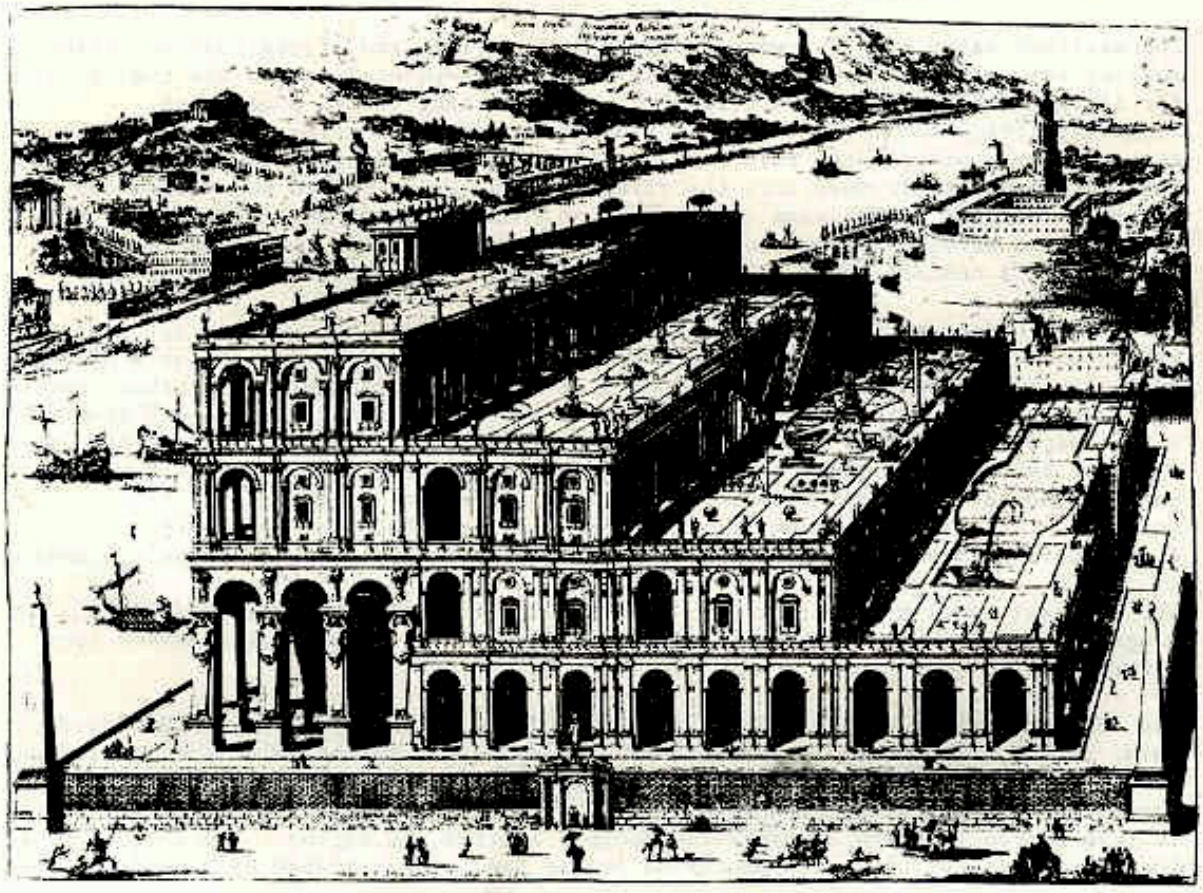

Fig. 7.1. The Hanging Gardens of Babylon (4000 B.C.).[15]

The earliest metal pipe, of copper, was found in the temple of King Sahura at Abusir in Egypt: it dates from *ca.* 2750 B.C. The piece is about 1.1 m long and 75 mm in diameter, and was formed from copper sheet lapped longitudinally. It may be seen in the National Museum in Berlin.

Another ancient water engineering triumph is to be seen in Jerusalem. Threatened by Assyrian armies in 701 B.C., King Hezekiah of Judah built a pool and a conduit, and brought water into the city (II Kings 20:20). A tunnel leading to the Pool of Siloam still pours sparkling water from Gihon Spring in Kidron.[38]

7.1.2 The Maya, Aztecs and Incas[11][23][42]

As long ago as 1500 B.C. the Maya of Central America are known to have had a flourishing civilisation which extended from the Yucatán Peninsula to the base of the mountains of Guatemala. As in other civilisations, adequate water supplies were essential. In some parts of Yucatán seasonal water-holes (aguadas) are to be found, but since the earliest days settlements developed round the *cenote*. These are circular sink holes, often quite large, formed by the collapse of underground caves, which are filled throughout the year by water percolating through the limestone rock.

The grandest of the Mayan cities, in the middle of the Petén, was the huge centre of Tikal (*ca.* 300 B.C. to A.D. 900), which once boasted upwards of 10000 inhabitants.

> "There are ten reservoirs at Tikal from which the Maya obtained their drinking water, one of which was perforce refurbished by modern archaeologists in lieu of any other potable source."

To the west, near the border with Mexico, is the site of Piedras Negras where has been discovered:

> "eight sweat baths, complete with stone-built hearths lined with potsherds, masonry benches for the bathers, and drains to carry off water used in the bath."

In A.D. 300, close to what is now Mexico City, stood Teotihuacán, one of the most important of the religious and civic centres of Middle American culture:

> "Seven square miles in area, it boasted plazas lined with palaces and avenues, paved with polished stucco and drained by an elaborate system of underground conduits."[4]

In A.D. 1325 the Aztecs began to build the city of Tenochititlan on an outcrop in the saline lake where Mexico City now stands.[26]

> "They built a city that two centuries later caused the Spanish invaders to gasp in astonishment and admiration. Canals laced the island city. Great causeways connected it with the mainland. Aqueducts brought water from the springs of Chapultepec.
>
> For the Aztecs it was a superlative site. The climate was mild. The soil was fertile. The mountainsides were cloaked with trees whose roots helped to hold the surplus from the area's seasonal rains, giving the city a water supply from never-failing springs."[9]

The civilisations of the Andes date from about 1400 B.C., though hunting communities can be traced back much further (*ca.* 9000 B.C.). The Inca Empire was established around A.D. 1100. As imperial organisers, the Incas may be rated alongside the

Romans, and like the Romans they excelled at engineering, building roads over 5000 km long, complete with suspension bridges. They also piped irrigation water through mountain tunnels. To grow food, whole mountainsides were terraced, and watered by elaborate systems of ditches and sluices, while oases were formed in the desert regions by conveying water in vast aqueducts from the mountains as much as 600 km away.(4)(39)

The capital city of the Incas was Cuzco (where the Huatanay River's paved channel brought water and carried away sewage), but the most famous of their strongholds is the fortress city of Machu Picchu, which reached its zenith around A.D. 1450. Located astride a mountain ridge some 2450 m above sea level, Machu Picchu's water supply has been described as "an ingenious procession of fountains". These roughly bisected the city and brought water within easy reach of a thousand or so inhabitants:

> "Led by stone aqueducts from springs about a mile up the mountain, the water was piped to the fountains through an intricate network of holes bored through the thick granite walls. A stream poured in at the top of each fountain so that women could fill their earthenware jars, then fed to a basin carved in the rock beneath and passed through a duct to the next fountain in the long cascade."(40)

7.1.3 Islam

In Islam the supply, storage and distribution of water is an essential part of the design of the mosque for "water is the vehicle of purification and enjoys an almost sacramental status".(41) The mosque has a courtyard fountain, often with taps for lukewarm water, and with low stools so that the user can isolate himself from the ritually impure floor. The elderly or infirm may be provided with other ablution facilities inside the mosque, often in the form of a colossal marble jar with basin and taps. Early examples of the skilful use of water, in fountains and in water-channels, include the Qarawiyyn Mosque at Fez in Morocco (begun 859), the Great Mosque in Seville (1171-6) and the Al-Firidawsi Madrasa at Aleppo in Syria (1243-47).

The palatial royal caravanserai at Ribat-I Sharaf (1114) lies in north-eastern Iran on the road to Samarkand. The surrounding landscape is desolate, which no doubt accounts for the huge cistern set below ground in front of the main entrance to guarantee a supply of water throughout the year. The caravanserai of Aliabad, between Teheran and Qum, illustrates the elaborate planning and degree of sophistication achieved by the 19th century in this type of establishment, with its hot and cold water pools, and latrines with separate facilities for men and women.(41)

Over the years, customary law in particular places, or the edicts of the ruler, established various controls relating to the siting and construction of buildings, and these included control of the building services:

> "Water and drainage regulations were necessary to ensure that there was not a mixing of the sewage with fresh water supplies. Where channels or streams led fresh water into towns, sometimes to the houses themselves, they were to be designed and regulated so that they could not be used for ablution purposes until the channel had passed the point beyond which fresh water could not be drawn, and from there the water continued on its way carrying off the sewage led into it. Where houses depended on wells, it was usually left to the inhabitants to ensure that sewage pits were not built in such a way as to foul the wells."(41)

Long before the reign of Islam, Istanbul had a water supply, and parts of it are still in use. Instead of bridges, the Byzantines used "suterasi" to convey water across valleys. Towers were erected at intervals across the valley floor. Water from a channel on the hillside was taken in a pipe to the base of the first tower, and then by a rising pipe to the top, where it flowed into an open tank. A pipe led to the base of the tower, across the valley and up the next tower to another tank. The same procedure was repeated at each tower until the valley was crossed, and the water allowed to flow into the next section of channel.(2)

7.1.4 *The Romans*

The application of the principle that water finds its own level was described by Vitruvius, but the Romans went beyond using only a direct gradient to convey their drinking water across valleys, for they developed an elaborate system of siphons.(53) But the outstanding examples of Roman engineering works are those to be seen in the lofty single arches of the aqueduct between Zaghouan and Carthage in Tunisia (A.D. 117-138) which ran for 141 km with a capacity of 31.8 million litre/day; in the double-tiered aqueduct at Segovia (*ca.* A.D. 10); and in the even more famous three-tiered Pont du Gard (*ca.* A.D. 14) which once brought 450 l/day to each citizen of Nîmes.(10)(22)

The Roman water supply was initiated by Appius Claudius Crassus in 321 B.C. to meet a steadily increasing demand, and in 144 B.C. the first overhead system, the Aqua Marcia, was built (Fig. 7.2). By the 3rd century A.D., the eleven principal aqueducts brought to the city some 200 million litres per day — about 200 l per person for all purposes including industry, fountains and baths.* By the 4th century A.D. Rome had 11 public baths, 144 public lavatories, 1352 public fountains and cisterns, and 856 private baths. At its peak Rome was supplied with something like 1350 litres of water per head of population per day.(54)

In constructing the water supply system, the Romans avoided the use of "high-pressure" pipe, using instead bridges to cross valleys. The incoming supply was taken to three reservoirs, one serving the baths, one the fountains, and the third private houses. Private supply was available as a concession on payment of a fee. Most Roman citizens had to rely on water carriers who drew water from the fountains. For distributing the water, pipes of earthenware, lead, wood and clay were used.

An insight into the Roman system is given by Frontinus, who was in charge from 97 to 104 A.D. Seven hundred personnel — surveyors, inspectors, masons, paviours, labourers, architects and plumbers, and administrative staff — were employed. A group of technicians calibrated the bronze nozzles used for metering, each nozzle being stamped with the rate of flow. (The method was soon discontinued, on account of the ease with which the device could be tampered with.) Frontinus measured the volume flow along the aqueducts and supply lines — 35% of the water was lost between the source and the consumer, due to leaks and faulty nozzles. The total supply at that time was 1200 million litres. Of this, 17% was used for industry, 39% for private purposes, and 44% on barracks, fountains, public buildings and baths. The Roman system was largely destroyed in A.D. 537 when the city was attacked, and it was only partially restored in the 8th century.

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*This figure is given by Robins.(49) According to an anonymous writer in *Sanitär, Heizung-technik*, the quantity was 700 l/person per day — a consumption which may be compared with 600 l/person per day in New York and the Ruhr in 1955 for all purposes, including industry.(2)

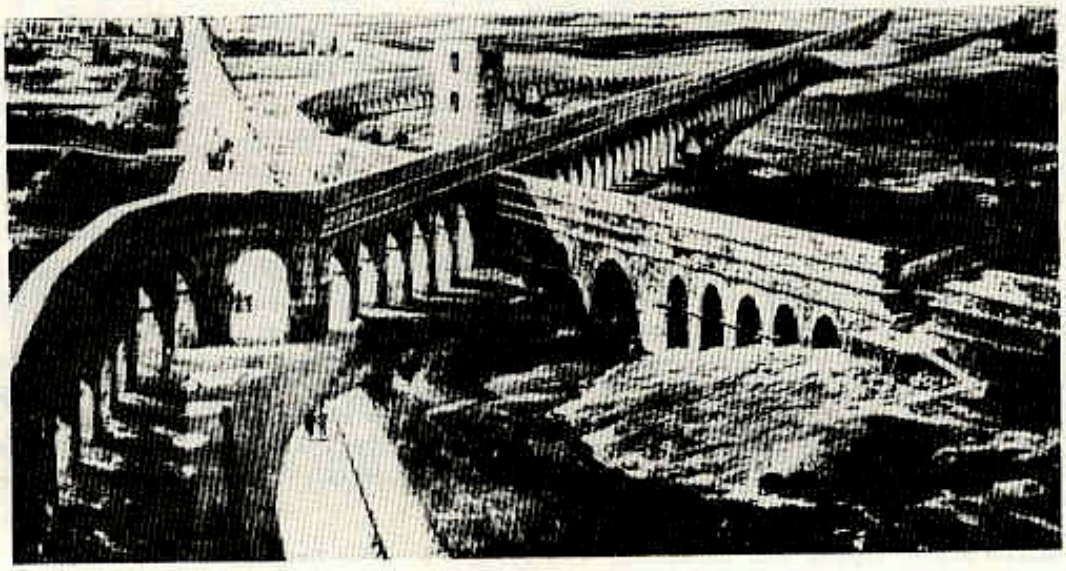

Fig. 7.2. Aqueducts outside Rome.
(Hodges, *Technology in the ancient world*)

The Romans installed the first piped supplies of water in Britain. Thus Lincoln was supplied by an aqueduct and carefully jointed pottery pipes. Wooden pipes have been found in other Roman towns (London, Silchester) and lead pipes in Bath.

7.1.5 Mediaeval times

With the decline of the Roman Empire, its expertise was largely lost in Europe, and for some centuries, less sophisticated methods of supply were employed, using mainly local sources of water. Outside the Roman empire, in Byzantium and Islam, the methods of water supply and sanitation were continued and developed, and

> "the recovery of material civilisation on the west depended on the Byzantine and other technologically more advanced societies farther east".(27)

Not until Norman times (1100 onwards) is there any record of piped supply to buildings in Britain, and then only to the very important ones. Robins writes:

> "In medieval Europe, such communal and social activities as were embarked upon were almost invariably under the aegis of the Church and especially the monastic orders.
>
> Water was rarely used for drinking save by the poorer classes. Washing was a more conspicuous habit in the religious houses than in secular establishments."(49)

The larger monastic houses (in England) collected water from springs or in reservoirs, and distributed it through pipes of wood, earthenware or lead. There were also usually underground sewers flushed by a flowing stream of water.(37)

> "A very early account exists of Ethelwold, Abbot of Abingdon, who is recorded as having made a water course (ductum acquae) in 960 which ran under the dormitory to the 'Hokke' stream. This was obviously an efficient diversion of a stream or a conveniently placed spring source, and is the first post-Roman account of sanitation in England".

More elaborate developments followed, and many a medieval monastery became the possessor of a "laver" or lavatory, which was a trough with running water, usually close to the refectory, where the monks washed their hands before meals or on leaving. Good examples of lavers of the 11th and 12th centuries are to be found at Durham, Dacre (in Cumbria), Goodrich (Herefordshire), at Gloucester, in Norwich and at Much Wenlock Priory (Shropshire).(7)(8)(35)(54)

In Canterbury Cathedral, the water works were carried out by Prior Wibert in 1160. Water was taken from springs outside the city, some 1¼ km from the monastery, to a circular conduit house, from whence it was conveyed through a perforated screen and several settling tanks by pipe to the city. Within the monastery, the water was taken underground to various offices and lavatories. Waste water went to a fish-pond and on to the "Prior's water-tub" where it was "joined by the waste from the bathhouse and the rainwater from the roofs, to provide a hearty cleansing flow through the main drain running under the 'reredorter' latrines". The original plans of the system still exist.

Some of these monastic systems remain in use. One conduit still serves the swimming baths of Sherbourne School; and the lead pipes at Lacock were in use in 1941. At Southampton, part of the friary water supply was for the use of the townspeople (*ca.* 1310). In 1420, the mayor and community of Southampton acquired the whole system, undertaking to supply both the town and friary. This remained the town supply until the beginning of the 17th century. An extensive system of tunnels under Exeter, dating from 13th century, acted as conduits for water supply to the city and the cathedral. In the 15th century, the Exeter authorities laid lead pipes from another source. Robins(49) gives a detailed account of the mediaeval supplies to many English cities. He notes, too, that there was a public, and publicly-owned, supply in Bruges in the 14th century.

From the 13th and 14th centuries, water supply systems were constructed in several important cities. Nuremberg was given a supply in 1361, via a network of wooden pipes, and only in the 19th century was the last of these replaced by cast iron.

While mediaeval Cambridge relied for its water supply on the local river, shallow surface wells and collected rainwater, there was one piped supply, that to the Grey Friars' House, said to have been carried in leaden pipes laid in 1327. Under Henry VIII the house of the Franciscans was suppressed, and in 1547 this pipeline was granted to Trinity College (where it still supplies the fountain in the Great Court). After the plague of 1574, another supply was obtained from Nine Wells, carried in a conduit planned by Edward Wright (1610).*(30)

London obtained its first water supply in 1237: the water was taken from a spring at Tyburn and distributed through pipes to a conduit at Cheapside, where the people could draw the water they needed. The Great Conduit of Chepe (Cheapside) was fed from Highgate, from where the Tyburn flowed down to a waterhead (now Stratford Place, Oxford Street). From here it was channelled through some 5.3 km of leather pipes to a stone basin (the Great Conduit) at the east end of Cheap for public supply. Another conduit built by William Lamb (remembered by Lamb's Conduit Street)

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*In later years the conduit came to be known as Hobson's Brook, after Thomas Hobson the carrier and wealthy Cambridge townsman.