Roman building services and architectural manuals: Part 2

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Introduction

This paper extends a previous paper [1], collecting and comparing material on a further selection of Roman building services – timber flumes, water supply tunnels, inverted water supply siphons, terracotta water pipes, and the *analemma* – across architectural manuals from the Roman and Renaissance periods. Transmission between these manuals, of ideas about these building services, is considered. Comparison is again made with the architectural record, to determine the extent to which these ideas were put into practice, and whether the manuals had a role in this. The two papers could be read together.

Roman sources include Vitruvius' *De architectura*, written 30-20 BCE [2], Faventinus, *De diversis fabricis architectonicae* (200-300 CE) [3] and Palladius, *Opus agriculturae* (c. 450 CE) [4]. Renaissance sources include Leon Battista Alberti, *De re aedificatoria*, printed 1486 [5], Sebastiano Serlio, *Tutti l'opere d'architettura et prospetiva*, 1537-1575 [6], and Andrea Palladio, *I quattro libri*, 1570 [7]. Vitruvian services not covered in either paper include wells (Vit. 8.6.12-13), cisterns (Vit. 8.6.14-15), and water-raising devices (Vit. 10.4-7).

Timber flumes

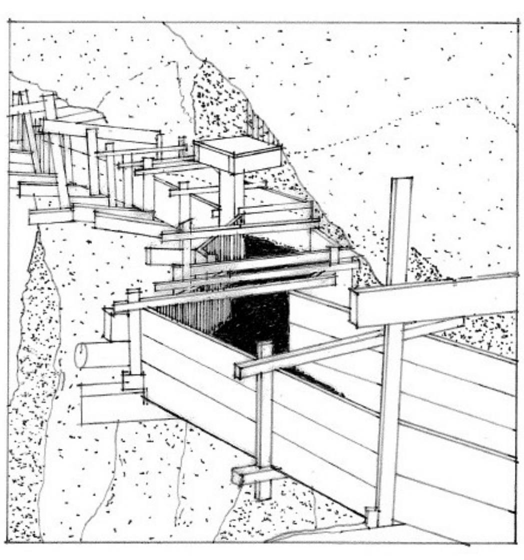

Figure 1: Part of the Ayent bisse.

Vitruvius listed three methods for carrying water, but timber flumes were not among them: 'Now for carrying water the three types are either watercourses through channels of masonry [i.e. aqueducts], or pipes of lead, or pipes of clay' (8.6.1). Faventinus added timber flumes to the list: 'structures of masonry, or pipes of lead, or pipes or channels of wood, or pipes of clay', and noted that 'channels and pipes of wood are seen as easy and common for carrying water'. Similarly, Palladius (9.11.1) wrote that, 'when water has to be led, this is done through a concrete channel or lead pipes or wooden flumes or earthenware tubes'. Timber flumes were clearly common.

For carrying water around hills, Vitruvius wrote that, where conveying water through lead pipes on a masonry aqueduct, 'if it is not far to go around, it should be led around' (8.6.5). Faventinus on the other hand suggested that 'a channel of oak for carrying water is constructed' (6) – much cheaper and quicker to build. Palladius suggested a channel to 'lead the water sideways round its flanks' (9.11.2), but did not specify the material. There is continuity between these authors, but because wooden channels or flumes were not mentioned by Vitruvius, they were perhaps a later technology. (Table 1)

Table 1: Methods of conveying water

Conveying water	**Vitruvius: 8.6.1**	**Faventinus: 6**	**Palladius: 9.11.1**	**Pliny the Elder: 31.31**
Masonry channels (previous paper)	Watercourses through channels of masonry	Structures of masonry	Concrete channel	-
Lead pipes (previous paper)	Pipes of lead	Pipes of lead	Lead pipes	Pipes of lead
Wood pipes & channels	-	Pipes or channels of wood – easy & common	Wooden flumes	-
Clay pipes (see below)	Pipes of clay	Pipes of clay	Earthenware tubes	Earthen pipes
Around hills	Lead pipes on aqueduct: 8.6.5	Channel of oak: 6	Channel: 9.11.2	-

Structures of this kind, wrapping around mountainsides, can still be seen in the *bisses* of Switzerland, used still to irrigate pastures and vineyards [8]. There are around 300, built from the 11th to the early 20th centuries. Their annual maintenance was a significant community tradition. Some of the earliest may follow Roman routes (e.g. Heido), and some date from the Renaissance. However, Alberti, Serlio and Palladio make no mention of them.

Water supply tunnels

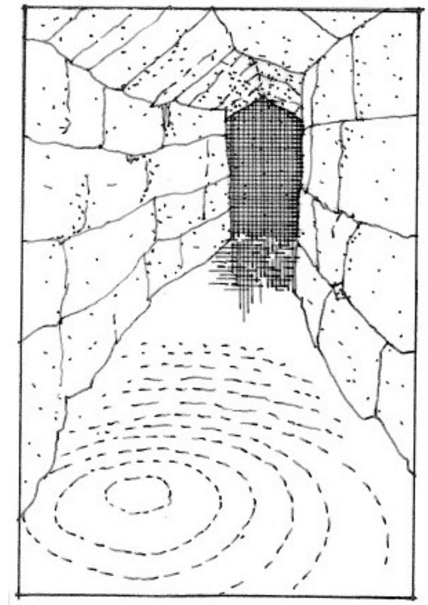

Figure 2: Arabic qanat at Palermo, Sicily, lined in masonry

Long before the Roman era, water supply tunnels were used for carrying water long distances. The underground *qanat* system to carry water from aquifers to its destination, used in Achaemenid Iran, Arabia and Egypt (and still in use today), is well-known [9]. An early example of a tunnel diverting water from a stream or lake is the 533 m Siloam (Hezekiah) tunnel serving Jerusalem, excavated in the late 8th and early 7th centuries BCE [10]. Greek examples include those at Athens, commissioned by Peisistratus (c. 535 BCE) [11], and at Samos (1.1 km), excavated by Eupalinos of Megaria (c. 530 BCE) [12].

Vitruvius (8.6.3) wrote that tunnels in tufa or stone should be cut into the rock directly, but tunnels in soil or sand should have built beds, walls and vaults (presumably of stone masonry). Faventinus (6) mentioned excavating an underground tunnel, and Palladius (9.11.2) mentioned tunnelling through the mountain, but neither described the construction.

The danger of suffocation underground was well-understood. Vitruvius (8.6.12-13) discussed the need for ventilation in wells. A lighted lamp was lowered into the well. If it was extinguished (by the vapours of sulfur, alum or bitumen, which cause suffocation), then ventilation shafts were required (also in Faventinus 4, and Palladius 9.9.1-2) [13]. Other authors raised the same issue, before and after Vitruvius, but with respect to mining:

- Theophrastus of Eresus (c. 371- 287 BCE) On fire, 24 [14].
- Lucretius (c. 99-55 BCE) On the nature of things, 6.808-815 [15].

- Strabo (c. 64 BCE-c. 25 CE) Geographica, 12.3.40 [16].
- Pliny the Elder (writing 77-79 CE) Natural history, 33.21 [17].

Vitruvius said that air shafts (which might also serve for setting out the tunnel during excavation, and for its maintenance) should be provided at an interval of one *actus* (120 feet = 36.6 m) [18]. Pliny the Elder (*Natural history*, 31.31) required access shafts every 2 *actus* (73.2 m).

Generally, in executed Roman tunnels the shaft spacing ranged from 30 to 60 m (98 to 197 feet), around one *actus* [19] as suggested by Vitruvius. But there are exceptions. For the 5.6 km drainage tunnel excavated by Claudius to drain the Fucine Lake (41-52 CE), the air shafts are on average 140 m (460 feet) apart, well beyond the recommendations of both Vitruvius and Pliny the Elder. The tunnel was lined in masonry as Vitruvius advised [20]. The longest known Roman water supply tunnel is in Syria, serving the 'Decapolis' and ending at the city of Gadara. It is 106 km long and took 120 years to excavate (commencing c. 90 CE). The air shafts are at every 20-200 m [21]. An inscription describing the excavation of a 428 m water-supply tunnel from both ends, at Saldae in Algeria in the 2nd century CE, survives. It was written by the tunnel's engineer, Nonius Datus. The tunnel appears to have had just the one shaft [22]. The depth of shafts also affected ventilation. At the Laurion mines in Greece, some are over 100 m deep [23].

It can be seen that Vitruvius was describing established tunnel technology, widely used in mining as well as for the conveyance of water. His recommendation on shaft spacing did not always reflect practice, suggesting his work was not a route for transmission. Subsequent Roman authors briefly mentioned tunnels, but dropped his technical requirements.

Alberti (10.7) more or less followed Vitruvius in his description of tunnel construction: '… wherever you find stone, tufa, dense clay, or any other material that does not absorb water, there will be no need to build anything; but wherever the bottom or walls are not solid, then some masonry will be necessary'. He suggested air shafts every 100 feet (30 m), with reinforced sides where the earth is not strong enough. Neither Serlio nor Palladio mention tunnels.

Agricola (1494-1555) described mining tunnels, shafts and ventilation, but did not follow Vitruvius at all, though he did recommend that miners understand architecture (Book 1) [24]. In Book 5 he gave the size of tunnels and shafts (2.29 x 1.14 m, and 1.83 x 1.22 x 23.79 m deep, respectively), and described their timbering where this was necessary. Air quality was certainly an issue and in Book 6 he described mechanical ventilation systems, such as bellows, fans, linen cloths, and wind sails. Provision of shafts for natural ventilation was not seen as a solution.

Water supply tunnels were built in the Renaissance. One example are the 'bottini' serving Siena in Tuscany, excavated from the 12th to 15th centuries over 25 km. These were designed and managed in part by the architect/engineer Francesco di Giorgio Martini (1439-1501), who wrote *Trattati di architettura, ingegneria e arte militare*, on this and other subjects. This drew on the work of Vitruvius and others, but had much original content, particularly on engineering. The 'bottini' still serve the fountains of Siena [25].

Inverted water-supply siphons

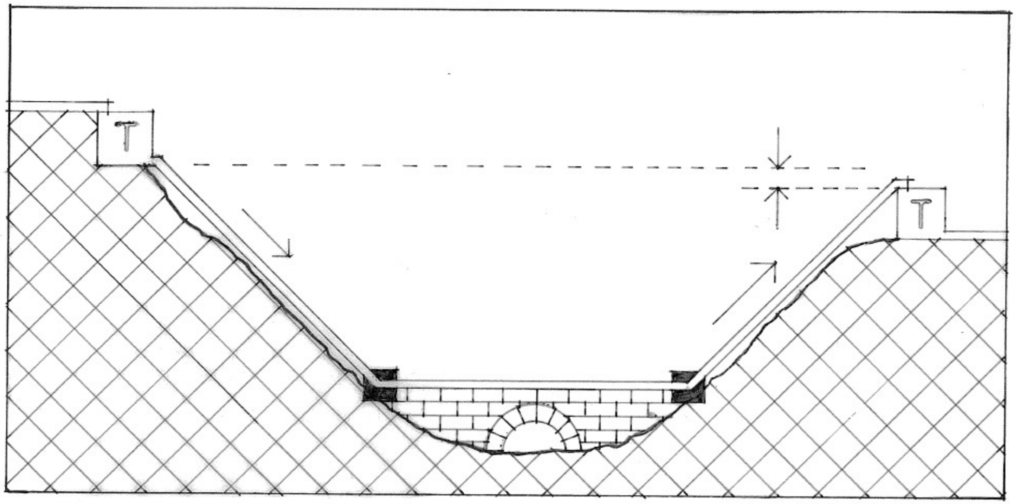

Figure 3: Inverted siphon.

An inverted siphon involves a water supply crossing a valley by running water in pipes down one side and up the other, from cistern to cistern, rather than across raised masonry channels at shallow falls [26]. At least 85 inverted siphons are known from the Greek and Roman periods [27]. While many used lead pipes, pipes made of terracotta, stone and even timber were also used. A Hellenistic example is the Madradag aqueduct serving Pergamon (Aeolis, in Turkey), probably built during the reign of Eumenes II (ruled 197-159 BCE). Two valley crossings were required and these were made with inverted siphons. The gradient was four times that of the steepest Roman siphon – the pressure at the lowest points (190 m deep) is estimated to have been around 1.52 MPa [28]. This pressure (from the weight of the water in the siphon, as well as the angles of descent and ascent), and the consequent requirement for water tightness, are the two main technical problems in the construction of an inverted siphon [29].

Vitruvius (8.6.5-6) described inverted siphons, using some otherwise unknown technical terms, and is the main written source on the matter from the ancient world [30]. He gave three options – channels on a masonry structure, channels wrapping around the hills, or inverted siphons:

> 'Next however, conveying water which is to be through lead pipes has this method of execution. When the source has a low gradient towards the city-walls, and the mountains between are not so lofty that they are able to obstruct, but have passes, it is necessary to build beneath, achieving a low gradient just as for streams and channels. Now if it is not far to go around it should be led around, but if there are uninterrupted valleys, the course will be directed down a slope [31]. With it approaching the bottom, [there is] a low substructure, such that a low gradient goes a very long way. This moreover is the intestine, which Greeks call *koilia* [32]. From there as it approaches the opposite slope, from the long distance of the intestine it gently turns upwards, to be raised to the height of the top of the slope.
>
> When an intestine in the valleys has not been made nor a substructure made to low-gradient, and instead it is a knee-bend, it [i.e. the water] will break-out and will weaken the joints of the pipes [33]. Also in the intestine

> *colluviaria* [34] are to be made, through which air-pressure can be relaxed. Thus through lead pipes which carry water, they are able to produce the best scheme – and they are able to realise this scheme due to the descent and being led around and the intestine and venting – where they have a slope at low-gradient from the source towards the city-walls'.

It has been argued that there is no need to relax air-pressure, as the pipes in a siphon contain no air. However, this is not the case – air pockets are likely to form in inverted siphons, causing energy loss and capacity reduction. The science remains poorly understood, but the use of air valves is normal practice [35].

Later authors provided much briefer descriptions. Faventinus (6) wrote:

> 'But if concave valleys impede emission, solid masonry or an arcade is provided at the level of the water, or pipes of lead or channels direct a free course. But if it will be at a high place, then water is carried somewhat lower cast on a flat curve, so that approaching water flows breaking impetus gently. Or if carried far from the mountain, make more winding flats'.

These are the intestines of Vitruvius. The mention of a 'high place' probably referred to the preference for siphons in deep valleys (above 45 m or so), over arcaded masonry aqueducts, as seen in the archaeology [36]. Vitruvius did not make this point. Palladius (9.11.2) advised that, where a valley intervenes, we can build a raised structure to carry the water, 'or allow it to descend enclosed in lead pipes and to rise on the far slope of the valley' – an inverted siphon. Pliny the Elder (31:31) provided a garbled description:

> 'Where rising, it will be on elevated works, carried in lead. It climbs the height of its source. If carried for a longer route, it ascends often and descends, so the forces are not wasted'. (author's translation)

The Romans appear to have used inverted siphons where a raised masonry channel would have been too costly and risky, being very high and possibly structurally unstable. Many examples are known, in Spain [37], and in France. Nine siphons were used in the aqueducts supplying Lyon, with up to a dozen parallel pipes per siphon – the total weight of lead used was between 10,000 and 15,000 tonnes, costly even to the Romans, but evidently still preferred to raised masonry channels in this case. The Beaunant siphon (123 m deep) on one of these aqueducts, the Gier (built during the reign of Hadrian), used perhaps 2030 tonnes of lead [38]. The Soucieu siphon (93 m deep), also on the Geir aqueduct, had nine 260 mm pipes, and was 1204 m long [39].

The Romans built a double inverted siphon at Yzeron, France (c. 20-10 BCE) and a triple inverted siphon at Aspendos, Turkey (2nd or 3rd century CE). These featured 'tank towers' on the crests of intervening hills, not mentioned in Vitruvius. Some blocks in the Aspendos siphon were fitted with stone plugs set in plaster, perhaps for maintenance, or to blow off in the event of pressure surges – maybe these are Vitruvius' *colluviaria* [40].

Alberti (10.7) mentions the use of pumps, siphons and buckets for removing water from a temporary enclosure in a river, but these were hand-held devices, not large-scale inverted siphons. Neither Serlio nor Palladio mention siphons. However, Martini does – a siphon or pump moved by bellows and another by levers – but again, not the inverted siphon of antiquity [41].

Terracotta water pipes

Terracotta water supply and drainage pipes are known from the Minoan city of Knossos, Crete (3200-1100 BCE). They were about 760 mm long, between 85 and 170 mm in diameter with a wall thickness of 20 mm, and were slightly tapered at one end and flanged at the other [42]. They were also used in Greek cities such as Athens (6th century BCE) [43].

Vitruvius addressed water pipes, describing both terracotta tubes (*tubuli*) and lead pipes (*fistuli*), arguing that the former are healthier (due to the harmful effects of white lead, as seen in the pallor of lead workers) and provide purer water (8.6.10-11). Faventinus (6) and Palladius (9.11) agreed, using the same arguments. All three authors described terracotta tubes, but Faventinus added a little detail which was copied by Palladius. Pliny the Elder also followed Vitruvius. Transmission of ideas between the three authors is clear. (Table 2) Quite a number of Roman *tubuli* survive [44].

Table 2: Terracotta tubes

Vitruvius: 8.6.8	**Faventinus: 6**	**Palladius: 9.11.2-3**	**Pliny the Elder: 31.31**	**Alberti: 10.7**
Walls at least 2 digits thick [45]	Walls at least 2 digits thick	Walls 2 digits thick	Walls 2 digits thick	Internal diameter at least 4 times wall thickness [46]
Ends tongued to fit into each other [47]	Each tube narrower at one end to fit into the next	Each tube narrower at one end to fit into the next	Box joints so upper pipe fits into lower	Tubes slot into one another with fitted joints
-	Joint width 1 palm	Joint width 1 palm	-	-
Coat joints with quicklime and oil	Coat joints with quicklime and oil	Coat joints with quicklime and oil	Smooth with unslaked lime and oil	Coat joints with quicklime and oil
Bends made in drilled blocks of red stone (saxo rubro)	-	-	-	Bends made in drilled blocks of red stone
-	When complete, pour in ashes in a little fluid to stop faults	When complete, pour in ashes in a little fluid to stop faults	-	When complete, pour in ashes in a little fluid to stop faults

Lead pipes and terracotta tubes for water were discussed in Alberti (10.7) who, like Vitruvius, preferred terracotta tubes and described them in some detail. As can be seen, much was derived from Vitruvius and Faventinus or Palladius. (Table 2) Terracotta pipes were not mentioned by Palladio or Serlio. Water pipes of various materials were widely used in the Renaissance, a famous example being the Villa d'Este (c. 1560) [48].

Analemma

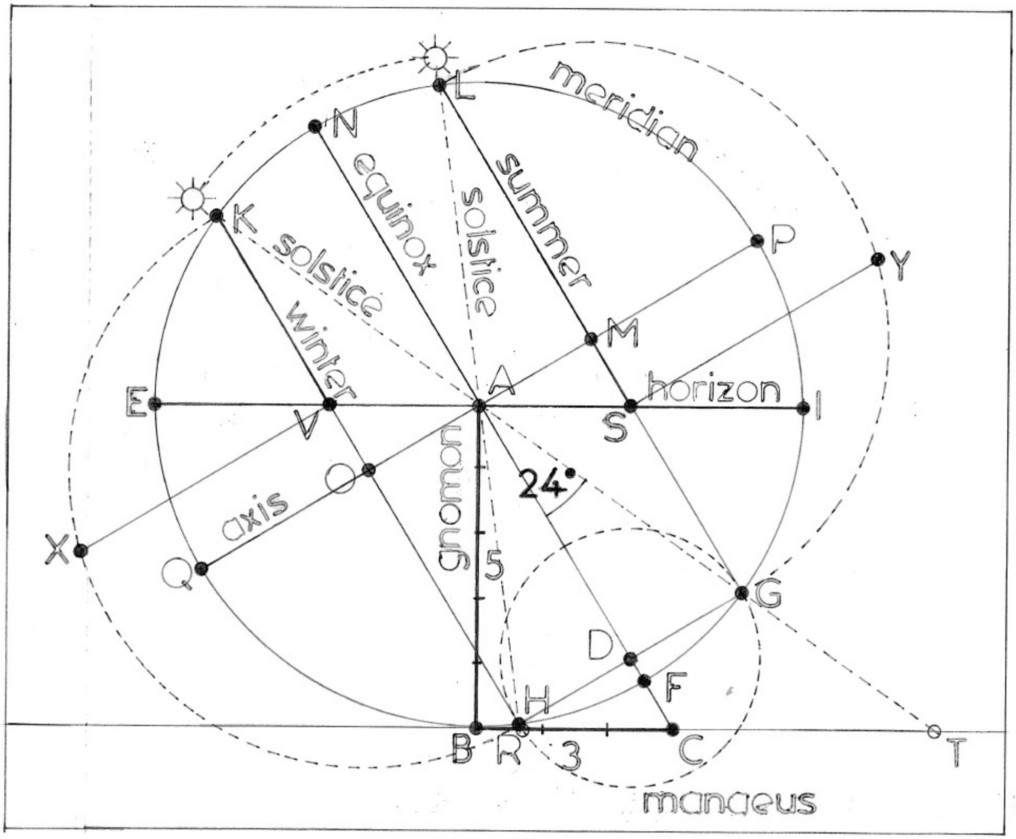

Figure 4: Analemma for Alexandria, after Vitruvius.

Knowledge of the *analemma* (a chart used in the preparation of sundials) came from the Hellenic world to the Roman. Pliny the Elder (2.78) credited the 'theory of shadows and the art of making sundials' to Anaximenes of Miletus (fl. c. 546 BCE).

Vitruvius (4.7) and Pliny the Elder (2.74) independently recognised the importance of latitude for the design of sundials, with an accuracy generally within 1°. (Table 3)

Table 3: Ratios of shadow length to gnomon height, noon at equinox

Location	Vitruvius	Pliny the Elder	Actual latitude	Ratio arctan	Error
Venetia	-	1/1	45.4°N	45°	-0.4°
Ancona	-	34/35	43.6°N	44.2°	+0.6°
Rome	8/9	8/9	41.9°N	41.6°	-0.3°
Tarentum	9/11	-	40.6°N	39.3°	-1.3°
Athens	3/4	-	37.9°N	36.9°	-1.0°
Rhodes	5/7	-	36.1°N	35.5°	-0.6°
Alexandria	3/5	-	31.2°N	31.0°	-0.2°
Egypt	-	A little more than 1/2	Thebes: 25.6°N	26.6°	+1.0°

Vitruvius went further, and wrote at length about the conic-section projective geometry of the *analemma*, used in the design of sundials. The principles were reasonably well understood, though perhaps not by Vitruvius himself, who omitted some details and did not explain how 'thus may it be transcribed and explained, either by winter lines or by summer or by equinoctial or even by monthly, on lower surfaces the methods of hours are transcribed from the *analemma'* (9.7.7).

But the *analemma* was not discussed by Faventinus or Palladius. Since Vitruvius (if not before) it had been the realm of the specialist, rather than the architect. Such specialists included:

- Diodorus of Alexandria (contemporary with Vitruvius);
- Hyginus Gromaticus (1st century CE);
- Hero of Alexandria (c. 10-70 CE);
- Ptolemy (c. 150 CE) in *Para analemmatos* [49]; and
- Pappus of Alexandria (c. 300 CE).
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Apart from Hyginus, all were from Alexandria, a key centre for the development and transmission of ideas. They did not use Vitruvius' description.

The remains of a Roman sundial maker's 'manual', incised on a stone fragment 110 x 127 mm, were found at Aquincum (Budapest) in 1990. This is in the form of an annotated master diagram for various latitudes, but not of Vitruvius' *analemma* [50].

The *analemma* was not discussed by Alberti, Serlio or Palladio. Instead writers on astronomy explored the topic, including Daniele Barbaro (1514-70) and Federico Commandino (1509-75) [51]. The *analemma* remained in the realm of the specialist.

Summary and conclusion

Transmission between the manuals of Vitruvius, Faventinus and Palladius was inconsistent – for the five services, transmission occurred four times and differently each time. On the other hand, the extent to which these technologies were put into practice in the Roman period was consistent – all were widely used. (Table 4) However, for none of the building services described here were the Roman manuals the route for implementation. At least four of the five services were in use before Vitruvius, and the standards – if any – long established. In any case, the descriptions of several of these services in the manuals were incomplete, inaccurate or vague. The Roman authors were out of their depth on siphons and *analemma* in particular.

Table 4: Transmission and implementation of ideas about building services

Building service	Transmission between Roman manuals	Roman implementation	Transmission to Renaissance manuals	Renaissance implementation
Timber flumes	Transmitted from Faventinus to Palladius.	Presumably widely used, latterly.	Not transmitted.	Some built, e.g. in Switzerland.
Water supply tunnels	Transmitted between all three, but with loss of information.	Widely used.	Alberti drew on Vitruvius, as did Martini.	Some built, e.g. under Siena.
Inverted water supply siphons	Transmitted between all three, but with loss of information.	Widely used.	Not transmitted.	None built.
Terracotta water pipes	Transmitted between all three, but varied.	Widely used.	Alberti drew on Vitruvius.	Widely used.
Analemma	Described in Vitruvius but not transmitted.	Used in sundial design – other authors describe it.	Not transmitted from Vitruvius – other authors relied on.	Developed further and used in sundial design – other authors describe it.

Transmission to the manuals of the Renaissance was sparse – Alberti drew on Vitruvius for just two of the services (water supply tunnels, terracotta water pipes). Of the others, the technology had been lost for one (water supply siphons), and technical development had been taken on by other disciplines for another (*analemma*). (Table 4) The Renaissance manuals were not a route for implementation for any of the services.

Transmission of ideas about building services between Roman and Renaissance authors does not follow a consistent pattern. The Roman manuals reflected contemporary practice on building services – they were not theoretical. Though their architectural components (e.g. the Orders) were enthusiastically adopted in the Renaissance, the Roman manuals were not a source for Renaissance building services practice.

References

[1] J.E. Gelder 'Roman building services and architectural manuals' in J.W.P. Campbell et al (eds.) *Studies in the history of services and construction: The proceedings of the Fifth Conference of the Construction History Society*, Cambridge: Construction History Society, 2018, pp. 31-42. This paper addressed aqueducts, lead water pipes, hypocausts, sounding vessels in theatres, sundials and water clocks.

[2] Translations in this paper are by the author, based on Vitruvius (transl. F. Granger), *On architecture: Books I-V*, LCL 251, Cambridge MA: Harvard University Press, 1931; Vitruvius (transl. F. Granger), *On architecture*: Books VI-X, LCL 280, Cambridge MA: Harvard University Press, 1934.

[3] Faventinus (transl. W.H. Plommer), *De diversis fabricis architectonicae*, in W.H. Plommer, *Vitruvius and later Roman building manuals*, Cambridge: Cambridge University Press, 1973 (UMI reprint 2001). Translations by the author.

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[8] A. Brenner, 'In the Swiss Alps, walking a cliff's edge to history', *New York Times*, 25 September 2019.

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[10] Rendsburg and Schniedewind (2010) believe that the tunnel was excavated at the time of Hezekiah. However, the dates are not certain – it might have been earlier. The 'Siloam inscription' records its construction, and is the only such record of public works from Israel or Judah: G.A. Rendsburg & W.M. Schniedewind, 'The Siloam Tunnel inscription: Historical and linguistic perspectives', *Israel Exploration Journal*, 2010, pp. 188-203.

[11] T.P. Tassios, 'Water supply of ancient Greek cities', *Water Science & Technology: Water Supply*, vol. 7/1, March 2007.

[12] Herodotus (transl. A. de Sélincourt), The histories, Harmondsworth: Penguin Books, 1996, 3.60, p. 178; K.D. White, *Greek and Roman technology*, London: Thames & Hudson, 1984, pp. 158-160. The Samos tunnel is now restored and open to the public.

[13] In modern terms, this is a performance specification with a method of test.

[14] M. van Raalte 'The nature of fire and its complications: Theophrastus' *De igne 1-10', Bulletin of the Institute of Classical Studies*, vol. 53/1, 2010 pp. 47-97.

[15] Lucretius (transl. C. Bailey) *On the nature of things*, Oxford: Oxford University Press, 1910.

[16] Strabo (transl. H.L. Jones) *Geography, Volume V, Books 10-12*, LCL 211, Cambridge MA: Harvard University Press, 1928.

[17] Pliny the Elder (transl. J. Bostock & H.T. Riley), *The Natural History*, London: Taylor and Francis, 1855.

[18] My translation is as follows: 'And so shafts shall be made, so that between two it is an *actus*.' The Latin of the last phrase reads: '*uti inter duos sit actus*'. Some translators (e.g. Morgan and Schofield) have misread this and given the interval as two *actus*.

[19] V. Labate, 'Roman tunnels', *Ancient History Encyclopedia*, April 2016. Online at www.ancient.eu/article/882/roman-tunnels (consulted 17 April 2018).

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[25] Gozzoli, A. '"I bottini" aqueduct', *Museo Galileo*, Institute and Museum of the History of Science, Florence, 2008. Online at https://brunelleschi.imss.fi.it/itineraries/place/BottiniAqueduct.html (consulted 28 November 2019).

[26] A siphon runs up a hill and down the other side. An inverted siphon runs down a valley and up the other side.

[27] Listed online at www.romanaqueducts.info/siphons/siphons.htm (consulted 27 April 2018).

[28] Hill, *A history of engineering* (Note 9), p. 28.

[29] C.R. Ortloff & A. Kassinos, 'Computational fluid dynamics investigation of the hydraulic behaviour of the Roman inverted siphon system at Aspendos, Turkey', *Journal of Archaeological Science*, vol. 30/4, 2003, pp. 417-428.

[30] Hero of Alexandria described siphons in *Pneumatics*, 1-5. Hero of Alexandria (transl. B. Woodcroft) *The Pneumatics of Hero of Alexandria*, London: Taylor Walton & Maberly, 1851.

[31] The three lead-pipe options presented here by Vitruvius are a raised aqueduct, a contour-hugging channel, and an inverted siphon. The Romans built the highly visible raised arcaded aqueducts because they were the preferred technical option for crossing a shallow valley. The water supplied was used by the public (baths, fountains, cisterns and so on) and by wealthy private citizens. It was both a utility and a luxury.

[32] 'Intestine' is chosen because both the intestine and this structure are very long tubes – this word emphasises the point. Gut, stomach and belly are among the alternative meanings, used here by other translators of Vitruvius, for both 'venter' and '*koilia*'.

[33] Pliny the Elder recommended the use of 'five finger' lead pipes at sudden changes in inclination, 'to break the impetuosity of the fall' (*Natural History*, 31.31).

[34] Translated variously as standpipes, water cushions, valves and dilations. Alternative readings have been suggested to support these translations (e.g. colliviaria, colliquiaria, collaxaria).

[35] I.W.O. Pothof & F.H.L.R Clemens, 'Breakdown of capacity reducing gas pockets in inverted siphons', *Water Science & Technology*, February 2006.

[36] White, *Greek and Roman technology* (Note 12), p. 214.

[37] I. González-Tascón, I, Bestué Cardiel & I. Velásquez, 'The organization of building work and construction of siphons in Roman aqueducts in Hispania', in M. Dunkeld et al (ed.) *Proceedings of the Second International Congress on Construction History*, Cambridge: Construction History Society, 2006, pp. 1305-1321.

[38] Hill, *A history of engineering* (Note 9), p. 30.

[39] Hill, *A history of engineering* (Note 9), pp. 38-39.

[40] G. Temporelli & F. De Novellis, 'Hydraulic engineering of inverted siphons in Roman age: A review', *Water Science & Technology: Water Supply*, vol. 10/3, July 2010.

[41] L. Reti, 'Francesco di Giorgio Martini's treatise on engineering and its plagiarists', *Technology and Culture*, vol. 4/3, 1963, pp. 287-298.

[42] A.N. Angelakis et al, 'Minoan and Etruscan hydro-technologies', *Water*, vol. 5/3, 2013, pp. 972-987; Hill, *A history of engineering* (Note 9), p. 27.

[43] HYDRIA Project, *The ancient Agora of Athens: Water works*, MIO-ECSDE, 2009. Online at http://www.hydriaproject.info/en/cases/athens/athenian_agora/importance.html (consulted 21 November 2019).
[44] Many museums hold examples, e.g. the Science Museum, London, object A167087 (100-350 CE), and at the Roman Museum of Nyon, Switzerland.
[45] A Roman digit was 18.5 mm, 1/16th of a Roman foot. Two digits are therefore 37 mm – thick by modern standards. Modern terracotta pipes of 150 mm internal diameter might have a wall thickness of 22 mm, and of 305 mm ID a thickness of 33 mm. Online at http://missionclay.com/band-seal-dimensions-and-specifications (consulted 17 April 2018).
[46] Should perhaps have read 'no more than'.
[47] The Latin is lingulati – tongue-shaped, tapered – but perhaps does not correspond to tongued in the modern sense of 'tongued-and-grooved'. Surviving tubuli show male-to-female end connections.
[48] D.R. Coffin, *The Villa d'Este at Tivoli*, Princeton: Princeton University Press, 1960.
[49] Survives in Latin only and involved the orthogonal projection of the celestial sphere on three mutually perpendicular planes.
[50] R.J.A. Talbert, Roman portable sundials: *The Empire in your hand*, Oxford: Oxford University Press, 2017, pp. 191-201.
[51] P. Fane-Saunders, *Pliny the Elder and the emergence of Renaissance architecture*, Cambridge: Cambridge University Press, 2016, pp. 213-214.