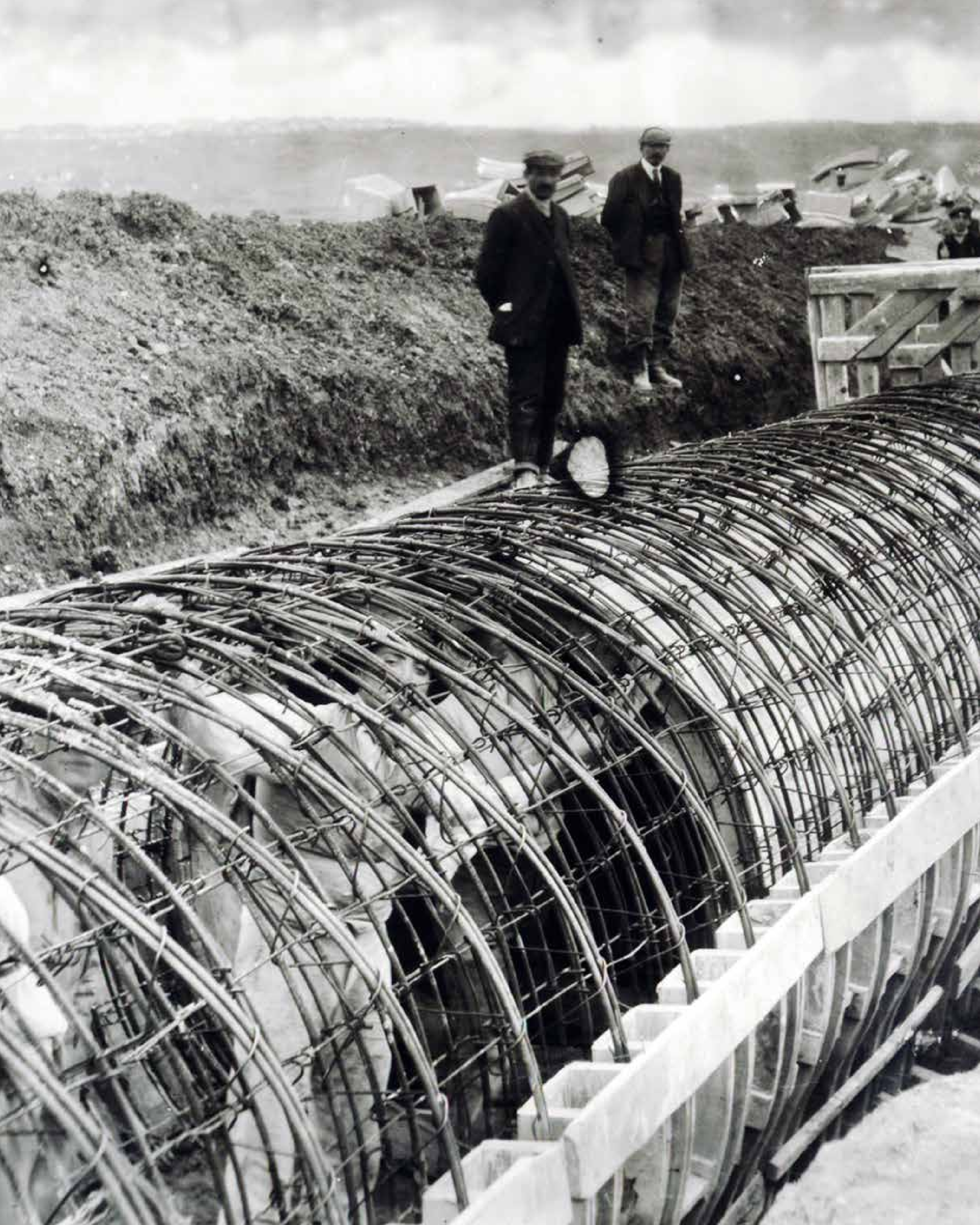

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A BRIEF HISTORY OF AQUEDUCTS AND CONDUIT RESISTANCE LAWS

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1 - INTRODUCTION

"If I have seen further, it is by standing on the shoulders of giants"

Isaac Newton was used to answer in this manner to those who asked him how he had managed to accomplish so much in the field of physics: "*If I have seen further, it is by standing on the shoulders of giants*". If even Newton acknowledged his debt to those who came before him, then, surely, we must also acknowledge the work of those researchers who conducted the first experimental studies of hydraulics, and to those engineers who pioneered the designing of aqueducts.

But who are these giants and why is it so important to have an adequate knowledge of the history of research in the field of fluid mechanics and the civil engineering profession? The reasons are many, but the main one is that a correct study of hydraulics, with its currently known laws, cannot do without those researchers and those projects that have turned engineering over the centuries from a form of art, often with empiricism as its only doctrine, into a science. Only by knowing the past can we better appreciate the legacy of those whose design formulas we use today.

Contents

The history presented here, which must necessarily be brief compared to the vast history of fluid mechanics in general, and of aqueducts in particular, is divided into six sections. The first is devoted to ancient investigations and applications of flows in channels and pipes. This is followed by a section devoted to a brief history of Roman aqueducts, still the object of much admiration today. It should be pointed out that, with the decline of the Roman Empire, the administrative capabilities necessary to develop and maintain such water systems was lost. It would be a long time before the kind of solution that the Romans had given to the problem could be taken up and applied again. Three sections are devoted to these issues, respectively on the history of flows from the Middle Ages to the 17th century, from the 18th to the 19th century and then to the most recent developments and studies, some of which are still being carried out at important internationally renowned universities. In particular, the history of aqueducts and the formulas underlying aqueduct designs refer to bibliographic data obtained from a vast literature, including the works of Rouse and Ince (1957), Rouse (1976), Pulci Doria (1980), Yen (1992), Griggs (1996), Wikander (2000), Wilson (2001), Brown et al. (2003), Viollet (2006) and Mays et al. (2007). The various references given in the bibliography will enable the interested reader to learn more about some of the issues discussed here.

Finally, following on from the story presented above, the last section takes a closer look at the particular case of the Apulian aqueduct, still an impressive achievement to this day and even more so at the time of its construction, the subject of international studies and comparisons due to the size and boldness of its engineering solutions.

2 – EARLIEST SURVEYS AND APPLICATIONS ON FLOWS

The Egyptians and the peoples of Mesopotamia

Some 6000-7000 years ago, the agricultural villages of the Near and Middle East were on the verge of becoming true urban centres. During the Neolithic period (between 5700 and 2800 BC) the first successful efforts to control the flow of water were dictated by agricultural needs (irrigation) in both Mesopotamia and Egypt (Butzer, 1976; Fahlbusch, 1996). As one of the world's rivers with the most regular cyclic variations, the Nile's floods were rarely sudden and abrupt, in contrast to the floods of the Tigris and Euphrates (Butler, 1960). Furthermore, the floods of the latter two rivers occurred in April or May, that is, too early for autumn sowing, since the summers were simply too hot. As a consequence, the ancient peoples of Mesopotamia needed to build canals to divert the flow of the rivers and to develop their agriculture. It is likely that the first large-scale diversions of water from rivers by humans originated in ancient Mesopotamia. Other hydraulic technologies of Mesopotamia were small water tunnels, water withdrawal systems based on the use of horses or donkeys and at least one large water diversion dam for agricultural use. The Nimrud Dam was built on the Tigris River about 180 km upstream from Baghdad. Water from the river was diverted through the Nahrawan Canal to irrigate an area some 100 km away from the present city of Baquba.

Irrigation with reservoirs, used in Egypt during the First Dynasty (around 3100 BC), involved flooding and draining fields with the use of sluice gates and containing water runoff by means of embankments built transversely and longitudinally to the waterflow (see Mays, 2008).

The Persians and the qanat

The *qanat* is a groundwater collection and conveyance system developed in Persia; the term is of Semitic origin and means "to dig" (Javan et al., 2006). The *qanat* consist of a series of vertical tunnels similar to shafts, connected by a gently sloping underground channel. This technique allows water to be drawn from an aquifer in such a way as to ef-

Figure 2.1.
Drainage channel at Knossos.

ficiently carry water to the surface without the need for pumping. In fact, the water flows thanks to gravity, since the destination is lower than the point of origin, which is usually, as already mentioned, an aquifer. The technique also allows water to be carried over long distances in areas with hot, dry climates without losing large quantities of the precious liquid to evaporation. The oldest *qanat* have been found in the north of present-day Iran and date back some 3000 years, when the Persians spread their use. This technology was widespread and eventually transferred to other civilisations, and is therefore also known by other names: *karez* (Afghanistan and Pakistan), *kanerjing* (China), *falaj* (United Arab Emirates) and *foggara* or *fughara* (North Africa). *Qanat* were built west of Persia, from Mesopotamia to the Mediterranean, and southwards in some parts of Egypt.

More on the ancient civilisations

The use of water briefly discussed above was mainly agricultural, but there is evidence of water sources used for drinking in urban centres during early civilisations, such as in the Bronze Age (4000-1100 BC), with the use of plain canals connected to rivers, rainwater harvesting systems, wells, rudimentary aqueducts and underground cisterns. In Mesopotamia, during the Bronze Age, the urban centres of Sumer and Akkud (third millennium BC) had canal systems connected to the Euphrates River, some of which were also used for navigation.

In the famous Sumerian city of Mari, female servants were tasked with filling the 25-cubic-metre cistern of the royal palace with water from a channel running through the city. Terracotta conduits were used in Habuba Kebira (in modern-day Syria), a Sumerian settlement in the middle of the Euphrates Valley in the mid-fourth millennium B.C. Mohenjo-Daro was a large urban centre of the Indus valley civilisation during the early Bronze Age, located about 400 km north of Karachi in present-day Pakistan. This city, built around 2450 BC, was served by at least 700 wells. In the third millennium BC, the Indus Valley civilisation already had baths in houses and sewers in the streets. The peoples of Mesopotamia were not far behind them.

Minoan civilisation

The Minoan culture flourished during the Bronze Age in Crete (Crouch, 1993; Cadogan, 2006). A systematic evolution of water management in ancient Greece began in Crete during the early Bronze Age, at the beginning of the Minoan period (around 3500-2150 BC). There were wells, cisterns, water distribution systems and fountains, also for recreational use. In the Minoan civilisation of the period between 2900 BC and 2300 BC, roofs and courtyards were also used as catchment areas for rainwater, which was drained to storage areas and cisterns.

Figure 2.2.
Part of the aqueduct constructed by the Athenian tyrant Peisistratos, excavated during construction of the Athens metro and now on display at Syntagma square, in Athens.

er, it is equally true that Roman engineers greatly improved the technology of water supply.

It should be remembered that the water supply system of Rome was unique at the time in terms of its size, but nevertheless the same public service was provided to many cities throughout the empire on a smaller scale.

From a technical point of view, two important Roman innovations need to be highlighted, represented by the construction of arches and the development of fast-setting concrete, whose characteristics of resistance and impermeability were highly appreciated, even when in contact with water.

The long, imposing arches built to lift aqueducts flat land or depressions can still be seen today in the Roman countryside, as well as in North Africa and various places in Europe. Although the

Figure 3.8.
Los Milagros aqueduct, Mérida, Spain.

4 – THE STUDY OF FLOWS IN CONDUITS FROM THE MIDDLE AGES TO THE 17TH CENTURY

Leonardo da Vinci

Leonardo da Vinci (Vinci, 1452 - Amboise, 1519) studied, among many other things, water flows in channels, writing a treatise on the subject (see Leonardo da Vinci, 1924). Although he made several mistakes, as our current knowledge has shown, his observations of the flow of water in channels were remarkably accurate. For example, Leonardo had a good understanding of the concepts of a riverbed's flow resistance and its repercussions on the distribution of velocity as a function of depth. He also had an understanding of what today is known as the continuity equation: "*The river gives passage in each part of its length in an equal time to an equal quantity of water, the river being of whatever kind it may be in width, or in depth; and this appears clear through its passing.*" It is worth remembering that in 1482 Leonardo da Vinci, having arrived in Milan, was commissioned by Ludovico il Moro to study a system that would allow navigation from Lake Como to Milan.

In general, during the Middle Ages, large irrigation and navigation canals were built from the 12th century onwards. The use of water wheels, which were also used to lift water such as the norias, became widespread. In the 17th century, the first piston pumps were built. Inventions from this period laid the foundations for the industrial revolution of the 18th century. For details on hydraulic researchers and engineers, see Hager (2003).

Galileo Galilei

Later on, fluid mechanics underwent further development with the contribution of Galileo Galilei (Pisa, 1564 - Arcetri, 1642), who introduced the so-called scientific method. Galileo did not hesitate to go against the established, typical ideas of his time, when his opinions were in accordance with experimental observation (Galilei, 1638). In order to ensure the reproducibility of experiments and of their measurements over time and across different settings, Galileo needed to establish standard units for measuring length and time. This provided a reliable basis on which to confirm mathematical laws using inductive reasoning. Galileo observed that two elements are required in the scientific method: 1) experience and 2) demonstration.

Benedetto Castelli

Further developments in fluid mechanics after the times of Galileo came about thanks to Bene-

Figure 4.1.
Benedetto Castelli.

detto Castelli (Brescia, 1578 - Rome, 1643), born Antonio Castelli, who was also a pupil and friend of Galileo (Figure 4.1). In his treatise "*On the measurement of running water*" Castelli was the first to state that "*the velocity of running waters decreases with the increase of the cross-section area through which they flow*" (Castelli, 1628).

Mariotte - 1686

Edme Mariotte (Dijon, 1620 - Paris, 1684), physicist and priest, was one of the greatest researchers in hydraulic experimentation, particularly with regard to flows in free-surface channels, and published his work in "*Traitté de la percussion ou chocq des corps, dans lequel les principales règles du mouvement, contraires à celles que Mr. Descartes et quelques autres modernes ont voulu établir, sont démonstrées par leurs véritables causes*" (1673). Figure 4.2 depicts Mariotte.

In particular, one of his works (Mariotte, 1686; details of the 1978 edition are also given in the bibliography) was originally published in 1686, shortly after his death, by his friend De la Hire, himself one of the most influential French scientists of the time ("*Traité du mouvement des eaux et des autres corps fluides, divisé en V parties, par feu M. Mariotte, mis en lumière par les soins de M. de La Hire*", 1686). Problems relating to flow rates in channels were addressed in Discourse III and Discourse IV, the latter devoted to the measurement of flows in aqueducts or rivers, of the above text.

In Discourse III Mariotte wrote that "*it is necessary to consider that the water of a river does not flow as fast at the surface and at other points, since the water near the bottom is much retarded by being in contact with stones, weeds and other discontinuities*". He had used wax floats to measure the time it took to move a certain distance down the river. Mariotte assumed an average flow velocity equal to two thirds of the velocity measured at the surface. He did not provide a functional relationship between depth and velocity, but the calculation referred to above suggests that he was aware that the relationship was not linear.

Guglielmini

Domenico Guglielmini (Bologna, 1655 - Padua, 1710) was one of the few scientists of his time to place great importance on mathematics even in the experimental sciences (Figure 4.3).

His fame in the management of fluvial waters led the Republic of Venice to entrust him with new tasks in the field of hydraulics. On his work in the field of hydraulics, see Guglielmini (1690; 1692; 1697; 1739; 1765).

Figure 4.2.
Edme Mariotte.

Figure 4.3
Domenico Guglielmini.

7 – THE CASE OF THE APULIAN AQUEDUCT

The need for the Apulian aqueduct and historical background

In the year it was opened, 1915, the Apulian aqueduct had the characteristics shown in Table 7.1, in which similar data is shown for three other more famous aqueducts of the same period.

It is worth giving some information, albeit briefly, on the need for the construction of the aqueduct and some historical background on it. Apulia, as is well known, is a region with low rainfall, with an average total annual value varying between 400 mm and 600 mm. Among other factors, the rainy period is limited to the cold seasons, while during the summer the rain is rare and typically intense.

The aridity of the region is exacerbated further by the formation and the geological makeup of the terrain, which is mainly made up of highly fractured limestone that rises, in the form of successive terraces, from sea level to the foot of the Lucanian Apennine chain, at about 300-350 m. Precisely because of this watershed conformation towards the sea, heavy rainfall flows very easily towards the Adriatic Sea or tends to penetrate the subsoil feeding the water table. The consequence of this particular situation in Apulia is the absence of surface springs worthy of mention. It is well known, for example, that in the Bari area the furrows of streams, known locally as "*lame*" (Mossa, 2007) often go from being devoid of water to almost sudden flood conditions causing serious damage to the surrounding areas (think of the historical floods that have affected the city of Bari). This water shortage in the entire Apulian region has earned it the historical name "*thirsty Apulia*". The population, who showed a special bent for agriculture until at least the 19th and early 20th centuries, had to collect rainwater in special cisterns for both domestic use and for livestock, with limitations on drinking consumption and agricultural production.

From this brief analysis, we can understand the strong need for an aqueduct to serve the Apulian region, which, however, presented several problems. Firstly, along the Adriatic side of the Lucanian

Table 7.1.

Main characteristics of the Apulian Aqueduct in 1915 compared with the main aqueducts of the time.

Name of the aqueduct	Catskill New York	Los Angeles California	Coolgardie W. Australia	Apulian Aqueduct
Length [km]	144	378	564	1598
Capacity [m^3/s]	26.8	11.0	0.3	5.5
Siphon or duct diameter [m]	2.77	1.80	0.76	1.70
Aqueduct source	Kensigo reservoi – Olive Bridge	Spring	Mundaring reservoir	Caposele spring
Year of opening	1914	1913	1913	1915

Figure 7.2. Caposele (AV). The Sanità springs in their original conditions, with the beginning of water capture works, around the year 1906.

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