Some Examples of Spanish Qanats

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Abstract

Shallow groundwater collecting systems by horizontal galleries, known by the Arabic voice qanats, have had a large development in Mediterranean Spanish areas (southern and eastern Iberian Peninsula). These systems have been used in order to supply water to cities or irrigated lands, from the 10th century to the beginning of 20th century, although there exist examples of possible roman construction too, extended during Arabian domination and in medieval and modern period.

Spanish name is “viaje de agua” (latin name deformation “via aquae”), and there are many examples of these constructions along spanish geography: in Barcelona there were many mines that start in Tibidabo base; Costa Brava (Gerona); Lorca (Murcia); Crevillente (Valencia); Granada; Puebla de Montalbán (Toledo); Córdoba; Ocaña (Toledo); Madrid and so on.

Madrid ones are the best studied of all of them, thanks to an exhaustive study carried out in the eighties. Madrid springs were a typical feature on urban landscape, and were feeder of “viajes de agua”.

During 17th and 18th century, and the first half of the 19th century, the “viajes de agua” were the main water supply in the village, as, although private houses had wells, these waters only were used for irrigation. Total length of “viajes de agua” was about 124 Km, 70 Km of which were collecting galleries and the other part conduction ones. Volume supplied was 3.600 m^3/day, which decreased over the years mainly due to a bad conservation service. In the middle of 19th century, the volume didn’t exceed 2.000 m^3/day. Location of these “viajes de agua” was in the superficial saturated zone, inducing a high vulnerability of the system during draught periods, and also to pollution in a city where the sewer system wasn’t properly developed yet.

Ocaña qanat, probably of roman age but with arabian and medieval elements, represents an incredible relic due to its 400 m of galleries and magnificent vaulted rooms. Qanat supplies the monumental “Fuente Grande”, herrerian style, declared national monument. Nowadays, it’s an excellent example – still on use- of famous ”viajes de agua”, that supplied Madrid until the middle of 19th century.

This work shows its hydrogeological enclaves and the constructive elements, emphasizing water management according to its chemist quality.

1. Introduction

Spanish Mediterranean areas (southern and eastern Iberian Peninsula) have highly developed shallow groundwater systems that collect and conduct water through horizontal galleries.

These systems, or qanats (a Persian term taken from the Arabic), have served to supply cities or irrigate lands from the Xth to the beginning of the XXth century. There are also some examples of possible roman origin that became extended during Arab rule and in medieval and modern epochs.

The significance throughout history of this type of water supply system is such that in May 2002, the UNESCO recommended its protection as a monument of world heritage.

The name given in Spanish to the qanat is “viaje de agua”, or waterway (possible from the Mozarabic “via aquae”, Oliver Asín, 1958). The many examples of these constructions include: several channels, or mines, in Barcelona commencing their course at tributaries of the Tibidabo river; and the qanats of the Costa Brava (Gerona); Lorca (Murcia); Crevillente (Valencia); Granada; Puebla de Montalbán (Toledo); Córdoba; Ocaña (Toledo); and Madrid – to name but a few.

Among the many qanats throughout the peninsula, those considered the most splendid and those most extensively investigated are the galleries found in Madrid. Investigations to date have been undertaken mainly through the cooperation of several organisations under the formal agreement of: “Technical and cultural collaboration for investigating the soil and subsoil of the Madrid municipal area“. This project was launched in 1982 by the Madrid City Council in conjunction with the Complutense University, the Spanish Ministry of Public Works and Urbanism (MOPU), the Planning and Coordinating Commission of the Madrid Metropolitan Area (COPLACO) and the Spanish Geology and Mining Institute (IGME). The project's main objectives were to characterise the geological and hydrogeological features of the area, to evaluate the water systems' potential, qualities and associated risks (as a water supply or as a reserve resource). A further aim was to select some of these geological-cultural resources on the grounds of their scientific, pedagogic and landscape features from a perspective of possible applications in conservation and/or teaching programmes (López-Camacho et al., 1986a).

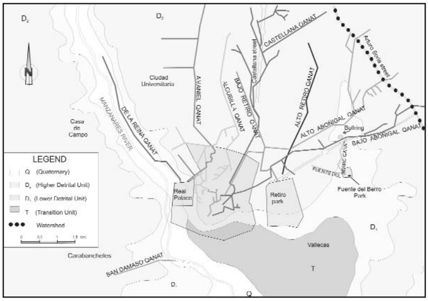

Figure 1. The main qanats of Madrid and underlying hydrogeological units

2. Madrid´s “viajes de agua”

From the times of Arab domination until the water company Canal de Isabel II (which presently supplies the city) was set up in 1858, groundwater was the sole source of water in Madrid.

Madrid's first settlement arose around the Matrice stream as a small Visigoth village. In the second half of the IXth century, Muhammad Ibn al Rahman founded Maŷrit, the northern fort of the Toledo kingdom, to ward off invasions from the north of the Iberian Peninsula. This led to a population increase such that the Matrice stream was unable to meet the demands of the city's 12.000 inhabitants. This deficiency was soon resolved by the construction of qanats (collecting galleries) to capture groundwater

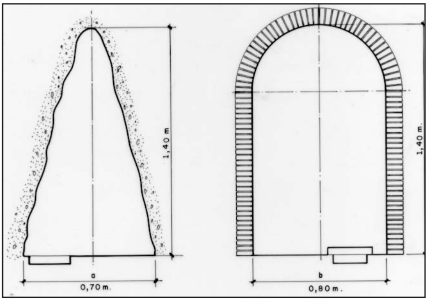

Figure 2. Fuente del Berro qanat. Horse-back gallery and lined, arched gallery

and conduct it to the city, where it could be distributed (via conducting galleries) through public fountains. Although there were wells in private estates, these were only used for irrigation purposes (López-Camacho et al., 1986b).

Most qanats rest on a detrital hydrogeological unit comprised of sediments that correspond to several facies of alluvial fan development, infilling the Fosa del Tajo on which Madrid is built. An upper and lower subunit have been identified (Figure 1):

The higher detrital unit is lithologically composed of more or less clean arkoses, southwardly increasing in fine grain content. The lower detrital unit is characterised by alternating arkoses and brown clays, and shows a similar decrease in grain size towards the south, accompanied by an increased proportion of mud.

There was also a series of hard-water qanats (not shown in Figure 1) in a transition unit composed of a set of lithofacies made up of carbonates, clays with flints, green clays, sepiolite and micaceous sands.

These channels were constructed by sinking wells until the saturated zone was reached. The wells were linked by galleries that also captured water, and were lined or left unlined depending on the consistency of the terrain. The starting points of these galleries were always to the north and east of the city and were separated by some 7 to 12 Km of 1% slope.

The galleries varied in shape and their size was such that a person could walk along the gallery. Depending on the terrain's conditions, the galleries were generally unlined and the shape of a “lomo de caballo”, or “horse back”, in cross-section. Others showed an arched section and were brick lined (Figure 2).

Water entered the collection galleries under the force of gravity, running either directly along the gallery floor (Figure 3) or along a side channel, or gutter (Figure 4). On arrival at the city, the qanats branched out to form a distribution network of conducting galleries. These are similar to the collecting galleries, but are lined and fitted with several possible

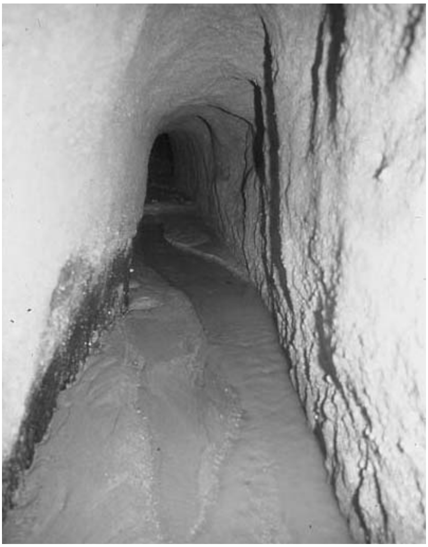
Figure 3. Horse-back gallery. Amaniel qanat

Figure 4. Side gutter. Bajo Abroñigal qanat

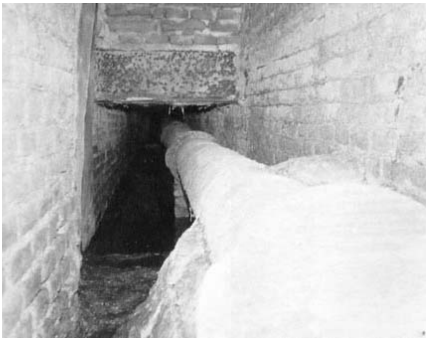

Figure 5. Cast iron pipe. Bajo Abroñigal qanat

Figure 6. Breathing well. Fuente del Berro qanat

Figure 7. Breather cap. Amaniel qanat

Figure 8. Breather. Alto Abroñigal qanat

Figure 9. Course of the Villamalea qanat (Alcalá de Henares, Madrid) indicated by breather caps

Figure 10. Course of the Rey qanat indicated by breathing wells

types of gutter systems (closed gutters, mud or cast iron pipes, etc. Figure 5).

The galleries made contact with the outside at certain points through aeration wells, or breathers (Figure 6) capped with a stone or brick cover (Figures 7 and 8). Often, the positions of these structures allow the course of the qanat to be mapped (Figures 9 and 10).

If the gallery had to change direction during its course, this was achieved by a "cambijas" or small box. Turbid water could be removed from the general flow at an "arca" or drain, that also served to sample the water in the qanat (Figure 11).

The course of the qanats came to an end at public fountains, where initially the water was collected by the people. This practice subsequently gave way to the trade of water-carrier, which soon became an essential feature of the water supply service, and was documented as such in 1950. Besides delivering water to each house, the water-carrier

Figure 11. Registry drain. Fuente del Berro

Figure 12. Roman (?) qanat. Plaza de los Carros

also ran errands, took on the duties of a fireman on rainy days when the streets became impassable and helped pedestrians cross the street (García Cortez, 1950).

The fountains of Madrid were a typical sign of urban landscape and included the famous fountains of: San Isidro, Fuente de la Salud in the Parque del Oeste (West Park), La Mariblanca, Fuente de la Alcachofa in Atocha, Fuente de los Once Caños, Fuente de la Reina, etc. Even the monument fountains of the Salón del Prado such as that of "Cibeles" or "Neptuno" were fed by these "viajes de agua".

The first gallery known, was one constructed along the course of the Matrice stream spring, which was made reference to in 1202 (Oliver Asín, 1958). There are also reports of an ancient, perhaps Roman, gallery that was discovered at an archaeological site in

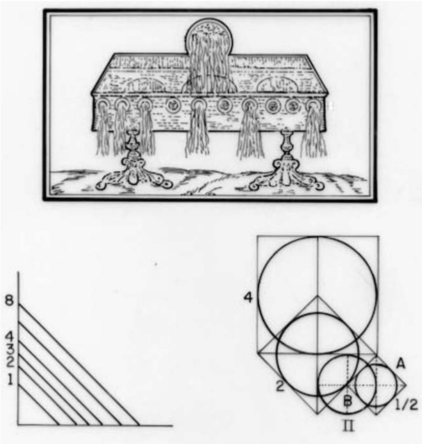

Figure 13. Discharge registry box (Ardemans, 1724)

the "Plaza de los Carros" (Figure 12). However, the first documented qanat is that of "La Alcubilla" (1399). From this date until 1855, in which the Fuente de la Reina was inaugurated, new conduits were opened until a length of 124 Km was attained, of which 70 Km were collecting galleries and the rest were conducting channels (Gil Clemente, 1911). Figure 1 shows the most significant qanats of Madrid that are still in use today.

As the Court was transferred to Madrid in 1561, the population amounting then to 14.000 inhabitants reached 46.000 in 1594 (Canal de Isabel II, 1954). This prompted the opening of several new galleries, which became a constant source of concern for the Madrid government, who set up a "Junta de Fuentes", or "Fountain Committee" in 1617. It was the task of this committee to search for new galleries, maintain and repair the existing system, and distribute the water and control its flow (Madrid Moreno, 1896).

Although there is record of isolated measures of the amount of water supplying the qanats since 1761, it was not until 1829 that discharge was systematically gauged on a two yearly basis (Archivo de la Villa, 1761 to 1880). Gauging was performed using the so-called "marcos de Madrid". These were metal boxes with one side perforated with holes of varying diameter (Figure 13). The amount of water passing through the holes in 24 hours gave the measure "real de agua".

This was defined by Ardemans (1724) as the water that emerges from a tube of the diameter of a "real de vellón", a copper coin pro-

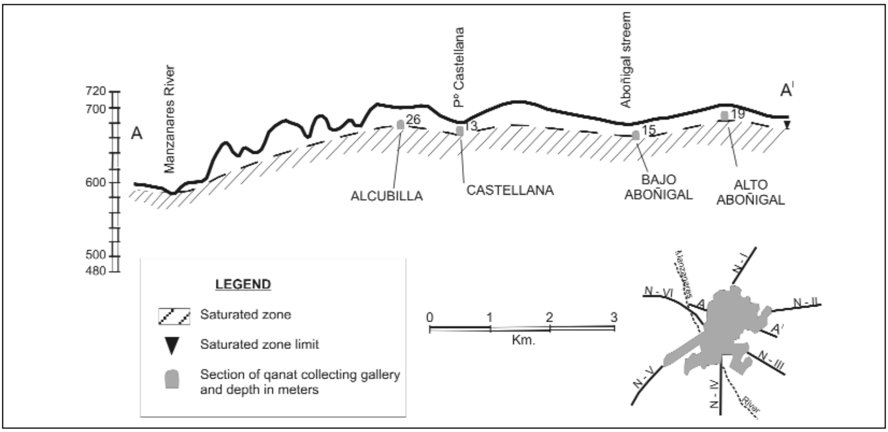

Figure 14. Hydrogeological profile of the qanats of Madrid.

duced in Spain in 1642. In 1727, Aznar de Polanco described the origin of the so-called “real de agua”, as the circle and area occupied by “un real de a ocho”, measured using the diameter of five silver coins. The measure is of no significance whatsoever, since the water velocity was not taken into account and thus its equivalence with the decimal metric system varies for each qanat (Aznar de Polanco, 1727). Madrid's water system supplied 3.600 m^3/day, which decreased over the years mainly due to poor conservation. By the middle of the XIXth century, discharge did not surpass 2.000 m^3/day (Canal de Isabel II, 1954). The depth at which the “viajes de agua” lay also posed restrictions on the water supply; their closeness to the surface of the saturated zone making them highly vulnerable to draught (Figure 14) (De Bustamante et al., 1986).

There is scarce information on water quality since it was not analysed on a routine basis. In some documents, there are references to the “softness of its waters”. Indeed, differentiation was made according to this property and qanats were described as soft- or hard water qanats. Aznar de Polanco (1727) made this distinction as a function of the weight of an “arroba” of water. On November 2nd 1852, the Madrid gazette published the first figures derived from the analysis of qanat water as concentrations in grams per pound of $MgCl_2$, $CaSO_4$, $CaCo_3$, $MgCo_3$, SiO_2 and $Al_2(SO_4)_3$. Water quality was related to the hydrogeological units crossed by the galleries. For example, the waters of qanats that only cut the higher detrital unit were described as soft, while those of the qanats crossing the lower detrital unit were “aguas gordas” (hard), such as the water of the Fuente del Berro qanat, still used today.

The Fuente del Berro, set in one of Madrid's most beautiful parks, is of great historic

Figure 15. Fuente del Berro

value due to its renowned waters that were consumed by members of the royal family and the inhabitants of Madrid since the times of Phillip IV (ca. 1631). Indeed, the park's appearance has changed through time according to the presence of the fountain and use of its waters.

The unique nature and fame of the water supplied by the Fuente del Berro is attributable to its dissolved salts. This property was conditioned by the presence of materials from the lower detrital hydrogeological unit, which cuts the channels and enriches its waters with magnesium and calcium salts, increasing hardness to around 100 ºF (French degrees).

The chemical composition of water samples taken from the northern and southern branches is shown below. It is of interest that today’s criteria for quality (e.g., the popular water from Lozoya has a markedly lower salt content and a hardness that does not reach 10 F) differ greatly from those defining the water that was so highly regarded by the people of Madrid for centuries (Table I, De Bustamante et al., 2001).

The water supply of the Fuente del Berro, which for centuries quenched the thirst of the “Madrileños”, was cut off in 1977 due to bacterial contamination. Its water was con-

Table I. Chemical composition of the water feeding the fuente del berro

	North Branch	South Branch
Cl- mg/L	57	28
SO4= mg/L	837	595
COH3- mg/L	268	256
NO3- mg/L	86	81
Na+ mg/L	55	49
Mg++ mg/L	85	73
Ca++ mg/L	261	200
K+ mg/L	4	4
TSD mg/L	1652	1.278
pH	7,1	7,0
Hardness ºF	100	80

sequently diverted towards the duck pond within the park. On April 16th 1983, after cleaning and repairing, the fountain was supplied with water from Madrid's main network, the Canal de Isabel II (Figure 15).

3. The qanat of Ocaña

The qanat of Ocaña, an admirable work of engineering of probable Roman origin with Arabic and Medieval elements, is an impressive relic due to its 400 m of waterways and magnificent domed chambers.

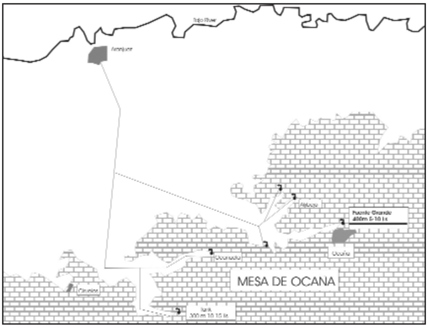

Figure 16. Location of the Fuente Grande and it captures (Aranjuez)

The fact that it is so well preserved is attributable to a set of circumstances. The main one is that it still constitutes a significant part of the supply route to the town of Ocaña (around 6.000 inhabitants). Further contributing factors are careful maintenance on behalf of the Town Council and perhaps, its connection to the spectacular Fuente Grande, declared a national monument in 1976.

Ocaña entered into the history of Spain as the Courts were summoned in the town by John II in 1422 and by Henry IV in 1468. Queen Elizabeth "the Catholic" resided in Ocaña for some time. Indeed, several renowned comedies by Lope de Vega and Calderón de la Barca are set in the town of Ocaña.

The town of Ocaña, or "Villa de Ocaña", has since the Middle Ages made use of its springs emerging from the scarps of two gullies in the meseta on which it lies (Figure 16).

Other surrounding springs (Ocañuela, Aljibe, Aldehuela) of the Mesa de Ocaña itself were captured to supply Aranjuez. The spring in Aljibe has a gallery of over 300 m in length, which in 1970, provided a discharge of 11 l/s. From 1745 onwards, all these galleries and springs were conducted

Figure 17. Main drain. Ocaña qanat

towards Aranjuez. In 1757, Ferdinand VI improved these conduits using glazed pipes from Madrid, and constructed many "arcas" or resting places for maintenance and cleaning (Madoz, 1845-50), some of which may still be seen (Figure 17). The hardness of the water collected does not reach an “F” value (French degrees) of 40, and contrasts with the quality of the water from the Tagus River close to Aranjuez, which is much harder and sulphated. This explains its capture and transport across a distance of over 10 km to supply the Real Sitio Palace and Mansion since the mid 1980s.

The Mesa de Ocaña is a practically horizontal plain of around 1.000 km^2 surface area, situated in the northeast of the Toledo province, some 60 km south of Madrid. Topographically, the meseta lies 100-150 m above its surroundings and is of an inverted trough shape. This morphologically characterises the geological formations of the paramos. Its highest points range from 700 to 800 m.

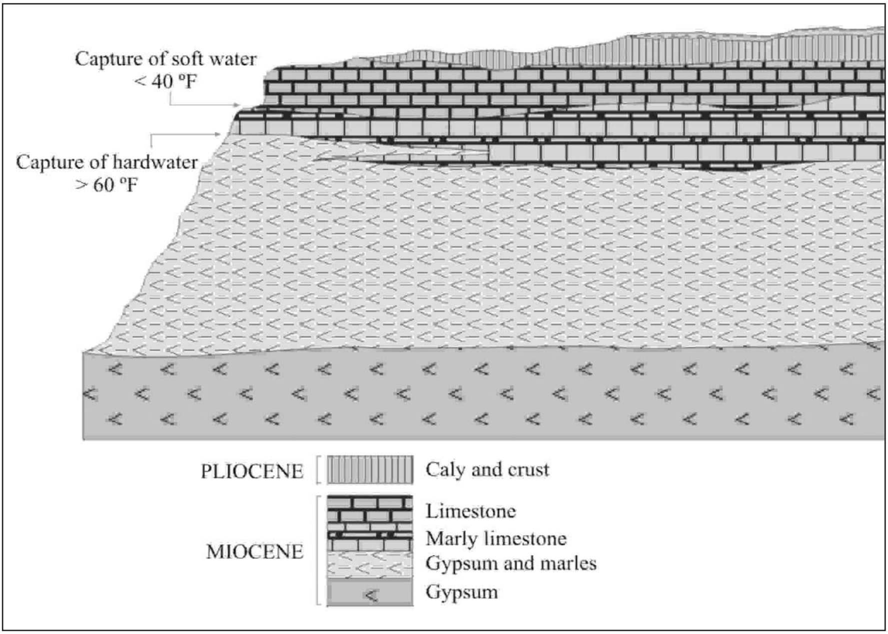

Figure 18. Geological cross-section indicating captures

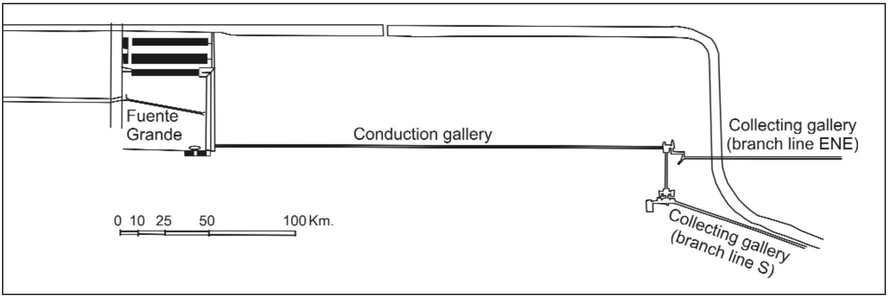

Figure 19. Fuente Grande de Ocaña qanat

Figure 18 shows a diagram of a cross-section through the Mesa de Ocaña, in which the different lithologies are represented:

a) a series mainly composed of gypsum with intercalated marls at the base (Miocene);
b) overlying this series are lithofacies formed of marl-gypsiferous materials at the base, that pass upwardly to marlaceous, marly limestone and calcareous materials (Miocene); it is the upper part of this calcareous or limestone facies that is captured by the galleries (Miocene);
c) a packet of white-reddish paramo limestones located above the water table; and d) generally clayey covering materials (Pliocene).

Figure 20. Well excavated at the southern branch of the Ocaña qanat

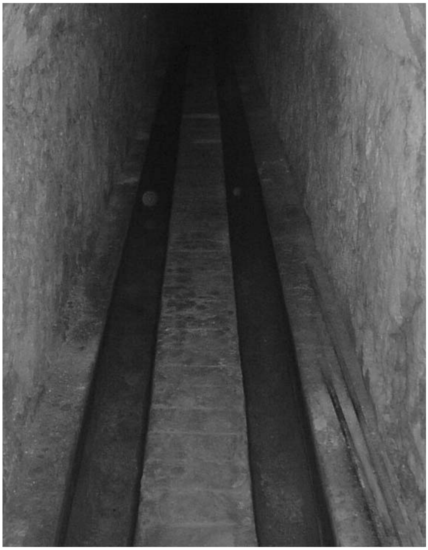

Figure 21. Conducting gallery with two channels carrying hard and soft water. Ocaña qanat

The Ocaña qanat ends its course at the Fuente Grande. The total length of the two main galleries is some 340 m. The main transport channel runs in an approximate W-E direction. The collecting channels bear 90 degree junctions (Figure 19); one that takes a south direction and another running ENE. Other branches have not been fully identified. The main gallery cross-section is 1.90 m high; its width ranges from 1.30 to 0.80 m. It is covered with a half-barrel vault.

Figure 22. Pumping station supplying Ocaña with water from the qanat

The southern branch is the main collecting gallery, due to its greater water supply since it also captures water from an excavated well (of turquoise coloured waters, Figure 20). Its waters are harder (around 70 ºF), since it crosses marly limestone materials and some gypsum. In contrast, the higher eastern branch captures calcareous stretches carrying softer water, and its water does not surpass a hardness of 40 ºF.

A peculiar feature of the Ocaña qanat is that the different types of water do not mix. In the main collecting drain (Figure 17), flows cross such that along the main gallery that conducts the waters from this drain to the Fuente Grande, the waters are delivered in two channels separated by a central passage: the soft waters of the ENE branch are carried by a lower channel, and along a parallel channel further north, flow the hard waters of the southern branch (Figure 21).

In the main transport gallery, some 80 m before reaching the Fuente Grande, the two small channels diverge and continue until they reach a 200 m^3 deposit at a depth of 5 m. Water is obtained by pumping upwards from this deposit to supply the inhabitants (Figure 22). Mixing of the waters gives rise to a hardness of 50-60 F. This point constitutes the access to the waterway from a group of houses built in the mid XIXth century to pump the water using steam-powered machines, which were subsequently replaced by the current electric pumps. Mean discharge provided by collection is around 500 m^3/day, insufficient to meet the needs of today's population.

Over the last years, this supply has been complemented with water of inferior quality obtained from a bore well close to the river Tagus, some 10 km away. Nevertheless, the fact that some supply from the qanat is still made use of has meant the survival of this surprising work of engineering (López Camacho and Iglesias, 2001). It is documented that in the XVIth century, an engineer – perhaps Baltasar de San Juan- or architect of Herreran formation, updated the old conduit (Madoz, 1845-50), which was probably of Arabic or perhaps Roman origin.

The main gallery of the qanat, with its two small channels transporting water of different quality, finishes its course at a fountain of Renaissance architecture, whose design is attributed to Juan de Herrera, the architect of El Escorial, and was constructed over the years 1573 to 1578.

Figure 23. Channels for water of varying hardness in the Fuente Grande

Figure 24. Livestock drinking trough. Fuente Grande

This impressive monument separately conducted soft and hard waters along pipes at different altitudes (Figure 23) to a large drinking trough used by livestock (Figure 24) and two huge washing pools, which could be simultaneously used by 300 washer-women (Figure 25).

Figure 25. Washing pools. Fuente Grande

The fountain stands in a large stone plaza of some 2.000 m^2 (Figure 26) and is accessed by a ramp and double masonry staircase. It is closed in its eastern part by a portico of 20 pillars that support a two-way roof. It is to this point that the waters from the gallery flow via 20 copper pipes (Figure 27). The

Figure 26. Fuente Grande

Figure 27.Bronze pipes. Fuente Grande

central part of the portico has narrow passes or port holes that act as overflows for runoff from storms, avoiding water accumulation behind the portico. Further, to avoid floods produced by heavy rainfall affecting both the land along which the qanat runs and the fountain itself, a millrace was built to divert the rain around the washing trough towards the fountains (Figure 28).

Figure 28. Rain channel. Fuente Grande

The waters are channelled in such an orderly, well-thought out manner, that the excess waters from the channels, troughs and deposits were collected and transported along a tunnel to the outside of the fountain to irrigate the neighbourhood crops.

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