Collecting, transporting and storing water in karst settings of southern Italy: some lessons learned from ancient hydraulic systems

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ABSTRACT

The karst landscapes of southern Italy, even though they show a lack or scarce presence of water at the surface, host a variety of ancient hydraulic works realized to collect and store water resources, to the advantage of the local settlements and for agricultural purposes as well. Ancient populations were forced to gain a deep knowledge of the territory in order to exploit the few available water resources, and developed for this aim several techniques, reaching a high level of capability to collect, transport, and distribute water, even at long distances. Many areas in southern Italy still nowadays present hydraulic works of remarkable interest and historical value, which are briefly described in the present paper, together with other features used for water storage in karst. Studying these ancient works, and safeguarding them, should be a priority aimed at educating the young generations toward a sustainable use of the water resource.

Key words | aqueducts, cisterns, hydraulic systems, karst, water

INTRODUCTION

Past civilizations often relied on the exploitation of water from large rivers: this was the case, for instance, in Mesopotamia with the Tigris and Euphrates, and in Egypt with the Nile river. In contrast to these examples, civilizations in the karst areas of the Mediterranean Basin (for instance, Greece, part of Italy, the Balkans), the Middle East and Asia Minor had to develop limited, often inadequate, natural water resources (Koutsoyiannis et al. 2008). Even when rivers were present, these were generally characterized by intermittent flow, which did not guarantee the required amount of water supply. The semi-arid climate was a further element responsible for water scarcity (Mays 2007; Endreny & Gokcekus 2009). All of this forced ancient populations living in karst to develop advanced hydraulic systems to collect and transport water to the inhabited areas. Types of hydraulic systems varied according to the local geological and morphological conditions, and resulted in: wells, underground aqueducts, reservoirs, cisterns; and in the collection, storage, and use of rainwater also.

Southern Italy is for large sectors characterized by soluble rocks (carbonates and subordinate evaporites), which makes karst the main process controlling the geomorphology and hydrogeology in the area. In karst, water is rarely present at the surface, due to rapid infiltration in the subsurface through the epikarst (Williams 2008). As a consequence, any settlement established in these regions had to solve the issue of water supply availability (Aley 2000). This was faced by means of a number of hydraulic works that testify to the impressive knowledge the ancient populations had of the local geology and hydrogeology. The present paper describes some of the hydraulic systems observed in the settlements and countryside in southern Italy, with a particular focus on the Apulia and Basilicata regions. These man-made works should be remembered; there is a lesson to be learned in terms of sustainable management, in following the way ancient populations adapted themselves to the characteristics of the natural landscape in which they settled and lived (Pike 1999; Parise 2011).
ANCIENT HYDRAULIC WORKS IN SOUTHERN ITALY

Aqueducts and drainage tunnels

Use of underground spaces to collect, transport and store water has a long history in Italy. Since Roman times, underground aqueducts were realized over the whole country to provide water to the main towns (Castellani & Dragoni 1991; Hodge 1992; Koloski Ostrow 2001). Ancient populations (and particularly ancient Romans) understood the relevance of placing the aqueducts underground as a method of protecting their fresh water from external threats, represented by the many enemies. The main advantages for building the aqueducts underground (Assante 2007; Tassios 2007; Parise 2009a) were represented by the possibility: (i) to conceal and to protect them from enemies; (ii) to protect them from erosion and deterioration; and (iii) to be less disruptive to life above ground. On the other hand, the main disadvantage in such a location was represented by the greater difficulties in maintaining and inspecting the systems.

These hydraulic works were derived from the qanats developed in Asia Minor, which is a gravity drained water supply system consisting of an underground tunnel that uses gravity to convey water from the higher elevations to the surface of lower lands, as a sustainable source for domestic, commercial, and agricultural water delivery (Mays 2007). A very important feature of qanat is that, being gravity drained, when they are designed with proper discharge rates and location they protect against aquifer over-extraction (Endreny & Gokcekus 2009).

In Iran, over millennia, 22,000 qanats were constructed, comprising more than 270,000 km of underground channels. Over the centuries, the technology was transferred to other civilizations, becoming known by different names such as ‘karez’ (Afghanistan, Pakistan), ‘kanerjing’ (China), ‘falaj’ (United Arab Emirates), and ‘foggara’ (North Africa). According to UNESCO recommendations, some of these hydraulic works are protected as monuments of world heritage (Laureano 1995; Mays et al. 2007).

The underground hydraulic works are really impressive when we think to the time when they were built, and constitute a precious testimony of the high engineering capability of the ancient populations. In Italy there is a very high number of ancient underground aqueducts, some of them being many kilometres long, with a mostly underground course. From these considerations, in 2005 the Italian Speleological Society started the project ‘The Map of Ancient Aqueducts of Italy’, entirely dedicated to studying and exploration of ancient underground aqueducts. As a matter of fact, ancient aqueducts have been for a long time explored and studied by cavers. Their importance derives from a number of historical, engineering, and environmental reasons: first of all, they represent a valuable documentation of the skill and engineering techniques of the ancient communities, and, due to the mostly underground development, have often been preserved intact for millennia. Further, if we take into consideration a concept which is nowadays considered very important, that is, sustainability in the use of the natural resources, ancient aqueducts are among the main works that testify to the efforts of man to manage the territory, and to develop urban civilizations without disturbing the delicate equilibrium of the natural environment. Many structures, even though lacking a continuous maintenance, are still functioning today, or might be put again to work through low-cost interventions, thus constituting an additional water supply during hydrologic crises. Thus, the observation by Koutsoyiannis et al. (2008), according to which the concept of sustainability should today be re-evaluated and revisited in the light of the ancient public works and management practices, becomes of particular significance.

So far, the project has resulted in collecting information on some 150 underground aqueducts in Italy (Parise 2009a; Parise et al. 2009). The great majority of the aqueducts, as expected, are located in Latium, due to the presence of the City of Rome. There, in AD 97, the engineer Sextus Julius Frontinus was appointed as imperial water commissioner (Curator Aquarum), being responsible for a supply of 800 megalitres daily into the city from nine underground aqueducts, covering in total a length of 420 km. As testified by these numbers, the underground engineering was deemed essential to protect the supply from contamination and from possible enemy action in Roman times.

Apart from Latium, practically all the Italian regions present some ancient underground aqueducts, whose location and length are dependent upon the local geology.
and morphology, besides having been dictated by position of the main sites (towns, settlement, military posts, etc.) that had to be supplied with water. Among the regions of southern Italy, Apulia hosts 13 aqueducts, covering all the provinces, the longest being the Triglio aqueduct in the Taranto area, reaching some 18 km in total length (Delle Rose et al. 2006).

Recently, efforts have been made, within the same project ‘The Map of Ancient Aqueducts of Italy’, to deal with other hydraulic works, which made possible the development of settlements and of agricultural practices in particularly difficult situations. This was the case, for instance, for the many engineering projects that were carried out to manage the land and regulate oscillations of lake level, by means of realization of underground tunnels (Galeazzi et al. 2015). Such hydraulic works especially characterize the areas surrounding several craters of volcanic origin in central Italy (Castellani & Dragoni 1991, 1997), but also interest the mostly karst landscape of Abruzzo, in the Fucino plain (Burri 1994). The system at the lake of Nemi, in Latium (Caloi & Castellani 1991; Castellani et al. 2003), is particularly worth describing: it is an example of an integrated structure for water control and irrigation, consisting of some 2 km of underground tunnels. The three tunnels and the related system of open channels, allowed control of the lake level, and use of its water as water supply to irrigate the Vallicella and the Cecchina locality (Figure 1).

Hydraulic works in urban sites

Underground aqueducts are without any doubt the most spectacular type of ancient hydraulic works, but many others may be observed in southern Italy. Many structures were related to the rupestrian culture, which particularly developed in Apulia and the nearby Basilicata during the Middle Age, and consisted in the establishment of settlements formed by houses and shelters carved in the rocks (Fonseca 1970). Due to the physical–mechanical properties of the Plio-Pleistocene calcarenite rock mass, even very complex, multi-storey, settlements were realized. Availability of water was, of course, crucial for the successful development of such sites. Given the karst nature of the area, with soluble rocks cropping out, water was rarely flowing at the surface, and this represented the most significant and serious problem for the settlers. In order to avoid such a problem, and provide the inhabitants with the necessary amount of water, a careful and sustainable use of the territory was developed by creating a system of transport and collection of the rainwater. The works realized at this goal are still today visible in many sites of the regions, and in particular above and along the flanks of the karst valleys: collection of water started from the plateau above the valley cliff, by means of a few tens of centimetre wide furrows dug into the rock. These served to let the water flow downslope, following a pre-ordained path until a tank or a cistern was reached. Underground storage was generally preferred, due to the fact that in this way the water was also kept at a cool temperature, which was very important, given the hot climates in this sector of Italy during the summer.

At many locations in southern Italy, the networks for water collection and transport were derived at least partly by ancient systems of channelization, dating back to the roman age and locally to the indigenous populations living even before the Romans. Efficiency of these systems, and the capability in planning and realizing them, is testified by the fact that a great number of towns maintain still today these features. Matera, in Basilicata, is without any doubt one of the most well known (Laureano 2001), which

Figure 1 | Sketch of the system of drainage tunnels at the Lake of Nemi (modified after Castellani et al. 2003).
in the 1980s was at the origin of its inclusion in the list of Cultural Heritage Sites by UNESCO. Matera was built in a territory characterized by valleys of combined karst and fluvial origin (gravine, in the sense described by Parise et al. 2003), with steep flanks carved into the calcarenite bedrock. Some of the districts of Matera (the so-called Sassi, meaning stones) were entirely realized within the rock mass, by digging artificial caves. These served as houses, shelters, stables, and were combined with other underground spaces properly realized for collection and storage of water. In some cases, a cave originally built to work as a cistern, was successively transformed into a house (Figure 2). The overall framework resulted in multi-storey settlements where the presence of sites to store water was essential to the successful life of the inhabited area. The underground cisterns were linked to the usual system of channels from the above plateau, in order to collect the maximum amount possible of runoff.

Many other sites in southern Italy share such a situation (Figure 3), with the historical part of town showing a high number of underground man-made cavities. Most of these were used to collect water, so that different typologies of cisterns can be observed (Maranò 2006). Their size reaches up to more than 10 m in height (Figure 4) and 4–5 m in width, with common depth values from 3 to 5 m. In most of the cases, cisterns were bell-shaped, but locally the shape slightly diverged, assuming a cone-shape, or a form more complex, with one side larger than the other. Cisterns were closed by a square rock with a central opening, through which the collection of water was carried out. At
the bottom, they often had a tank in order to let impurities deposit there; periodically, the tank was cleared of sediments, to allow the full use of the cistern. The cisterns were coated in plaster to make them waterproof.

One of the most spectacular examples is the Piscina Mirabilis at Bacoli, in the Phlegrean Fields of Campania (Figure 5): it is among the largest Roman reservoirs, with a capacity of 12,600 m$^3$ of water (De Feo et al. 2009). The cistern was supplied by water from the Serino aqueduct that was built from Serino to Miseno under Augustus, probably between 33 and 12 BC. The Serino aqueduct, 96 km-long with seven branches, was essentially built to furnish water to the Roman fleet based in Misenum, and to supply water for the demand of the important commercial harbour of Puteoli as well as drinking water for big cities such as Cumae and Neapolis (De Feo & Napoli 2007; Del Prete & Varriale 2007). The total drop in elevation from the source, the Acquaro-Pelosi spring in Serino, to the Piscina Mirabilis is 366 m (0.38%). The cistern is 72 m by 27 m in plan, and 15 m deep (Tolle-Kastenbein 1995; Hodge 1992).

Hydraulic works in rural areas

Apart from the hydraulic works realized to provide hydraulic supply to towns and settlements, water availability was necessary for ancient populations even in rural areas. These being mostly dedicated to pasture, water collection was there much more complicated. An important feature in the countryside of Apulia and Basilicata is represented by 1–1.5 m-high and slightly more than 1 m-wide dry-stone walls that dot the fields with long alignments; built using the local Cretaceous limestone, and without the use of mortar, dry-stone walls had several functions. Besides serving to delimit the fields and properties, and to keep the livestock within certain properties, they also worked as water collectors (Laureano 2001; Parise 2009b): the stones were carefully placed, to produce an inner gradient which allowed water to be kept inside the wall. A micro-climate, fresher than the surrounding areas, was thus created, which allowed the development of vegetation at the wall boundaries. Even small amounts of rainwater were in this way preserved by the intense...
evapotranspiration which characterizes most of the countryside during the hot day light hours, thus allowing development of a micro-climate within the dry-stone wall, and in its immediate surroundings.

In rural areas, the use of underground water storage sites was not an easy task. However, at specific sites showing peculiar geological and morphological features, wells and/or cisterns were often realized. This is the case for the area around the town of Conversano, in central Apulia, where ten seasonal lakes of karst origin are present (Lopez et al. 2009). The territory is characterized by carbonate rocks, generally at the outcrop or covered by thin residual deposits, and morphologically expressed by an uninterrupted succession of endorheic basins, karst valleys and dolines. Deposition of eluvium at the bottom of the dolines ended up by more or less completely blocking the fissures and the karst conduits and shafts, a condition which favours the formation of seasonal karst lakes, covering areas from 1,000 to 11,000 m², and bounded by small scarps in the surrounding calcareous rock. The lakes differ also in terms of the size of the standing water bodies.

Until a few decades ago, the lakes were the only natural water resource easily available to the local population who, in order to use it during the dry season, built numerous wells in the most depressed zone of the doline, aimed at recovering the volumes of water withheld by the continental deposits. The wells were internally coated with dry-stone walls. The number of wells in each lake ranges from a minimum of 5 to a maximum of 31; they have a bell-shaped section, whilst the depth is variable. Infilling deposits of the lakes consist of residual deposits ranging from silty clays (terre rosse) to silty sands, with local intercalations of volcanioclastic materials. Interlayering of deposits with different degrees of permeability, resting over an intensely fractured and karstified carbonate bedrock, makes these materials the recharge area for the underlying aquifer in the Mesozoic limestones (Figure 6).

Since antiquity, the temporary lakes of karst origin at Conversano have represented a resource of inestimable value for the local population, due to lack of surface water resources in the area.

As regards their origin, the ten karst lakes at Conversano may be subdivided into three groups, based upon the local morphology: (1) a group having tectono-karstic origin, which includes those lakes located in valleys bounded by faults or important tectonic lineaments; (2) a group of
erosional–karstic origin, with the lakes located within the lines of the ancient natural water network; and (3) a group of karstic origin, that is, the lakes occupying (entirely or in part) the bottom of collapsed dolines.

All the lakes have been historically modified by man, who tried to take advantage of the natural situation leading to presence of water at the surface or at a maximum in the first few metres, by realizing the above described deep bell-shaped wells. The importance of the lakes, besides the geological and hydrogeological interest, lies in the role they had in influencing the location of the first human settlements in this territory (Parise et al. 2009c). Protection of these sites, and of the ecosystems present therein, should be pursued in order to safeguard the karst landscape and the resources it contains, primarily the water.

Still in rural areas, it is worth citing the example of Masseria Lonoce at Grottaglie, in the Taranto province (the term masseria indicates the typical countryside mansion in Apulia, built using the local carbonate rocks). Masseria Lonoce is located in a slight karst valley (lama, after Parise et al. 2005), and hosts several artificial caves, realized for a variety of utilizations. These are very well integrated into the surrounding natural landscape, dominated by outcropping of carbonate rocks, and therefore by scarce presence of water at the surface, as is typical in karst. At the site, where during the different epochs several working activities were carried out, from olive oil production to cheese production, the need to have available water was met by creating a complex system of channels (Figure 7) to collect and let the water flow toward storage sites, mostly consisting of underground cisterns (Fornaro et al. 2008).

Similarly to what is observed at Masseria Lonoce, in many other sites of Apulia where ancient settlements developed, or where in more recent times human activities were
carried out, systems for water collection, transport and storage are present, locally being still used for the purposes of agricultural practices. The rupestrian settlements at Macurano (Sammarco et al. 2008) and near Capo di Leuca, at the southernmost tip of Apulia (Sammarco & Parise 2011) are further examples in this sense.

CONCLUSIONS

The description of some ancient hydraulic works and structures of southern Italy presented in this contribution points to the importance of remembering such works: not only do they represent remarkable evidence of the sustainable use of fragile territories such as karst, but many works are still functioning, and could be used to face the droughts and water crises periodically happening in these areas. Further, they represent a lesson to be learned for the sustainable use of the land, and of the natural resources therein contained. In fragile territory as karst, this issue is very significant, and local populations nowadays should pay greater attention to the careful use that past civilizations had of the karst lands. Rather than trying to exploit the natural resources with modern technology, protection of karst should be the priority, to avoid loss of unrecoverable and precious natural ecosystems, with particular concern for the life species and the water contained in karst.

It has also to be noted that the importance of management in drinking water supply is often underestimated in karst. In absence of a proper management, disasters can occur, even with the most modern treatment plant. Deficiencies in water supply management have often been a recipe for disasters, because of the direct and cyclic nature of the routes of transmission of waterborne disease (Pike 1999). Availability of water in the future, as well as its quality and distribution, are also affected by global warming, which is considered to be a definite threat to water resources (Sen 2009). All of the above considerations highlight the need to keep studying the ancient hydraulic works, in an attempt to move toward a better management of water resources, in particular in fragile territories such as karst.

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