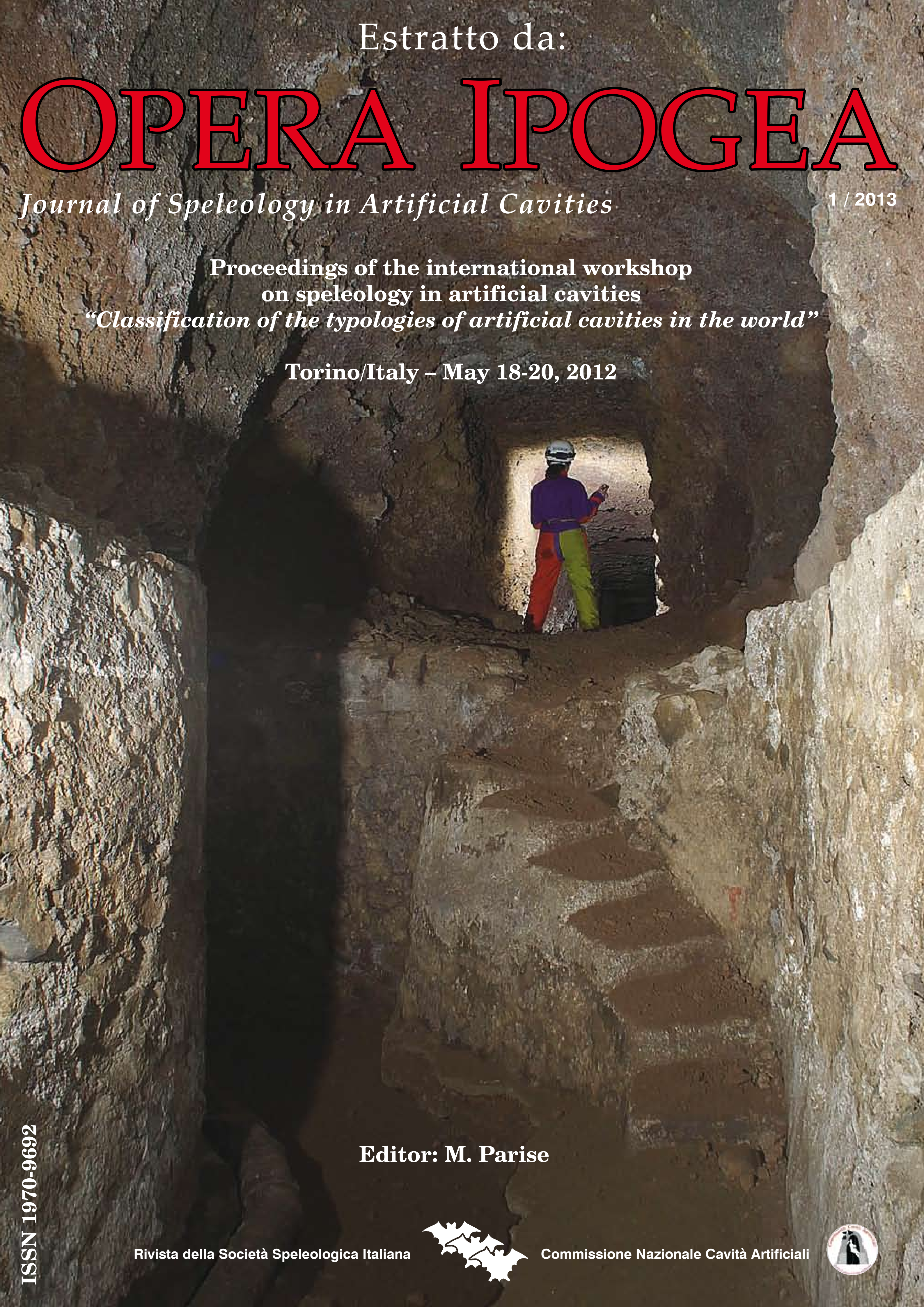

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Hydraulic works: the Map of the Ancient Underground Aqueducts

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Abstract

Among the many different typologies of artificial caves, hydraulic works deserve a particular attention, being strongly related to past history and civilization. Without the availability of water, development of settlements and villages, and establishment of a geographically stable inhabited area were not possible. Starting from these considerations, in 2003 the Commission on Artificial Cavities of the Italian Speleological Society started the Project "The Map of Ancient Underground Aqueducts in Italy".
Italy presents on its territory a huge amount of hydraulic works, showing very long underground stretches, that represent a valuable documentation of the skill and engineering techniques of the ancient communities. Due to their mostly underground development, they have often been preserved intact for millennia. During these years of work, we have been able to collect a great amount of material and information about underground aqueducts, through both direct caving explorations and analysis of the available documentation; a detailed register of ancient underground aqueducts in Italy has been thus realized, aimed at safeguarding these unique works of historical and hydraulic engineering importance. So far, more than 140 underground aqueducts, distributed all over the Italian territory, have been identified and studied.
In addition to aqueducts, other hydraulic works have also been studied within the project framework: namely, underground drainage tunnel realized for land reclamation purposes and/or for agricultural practices. The Project has been advertised through presentations at several Italian and international conferences, and with a number of publications, including special issues of the journal Opera Ipogea, entirely dedicated to the project (in 2007 and 2012). A detailed bibliography has been built, with reference to underground hydraulic works in Italy, and is being continuously updated. The bibliographic list is subdivided on a regional basis, and, within each region, is in turn divided for each single hydraulic work.

KEY WORDS: artificial cavities, underground aqueducts, hydraulic works.

Riassunto

OPERE IDRAULICHE: LA CARTA DEGLI ANTICHI ACQUEDOTTI SOTTERRANEI

Tra le varie tipologie di cavità artificiali, le opere idrauliche meritano un'attenzione particolare, in quanto fortemente legate alla storia e cultura del territorio. Senza disponibilità di risorse idriche, infatti, la fondazione e lo sviluppo di insediamenti antropici duraturi nel tempo non è possibile. Partendo da tali considerazioni, nel 2003 la Commissione sulle Cavità Artificiali della Società Speleologica Italiana ha avviato il Progetto "La Carta degli Antichi Acquedotti Sotterranei in Italia".
Il territorio italiano presenta un'enorme quantità di opera idrauliche, con significativi tratti in sotterraneo, e che rappresentano una documentazione di estrema importanza delle capacità e tecniche ingegneristiche delle antiche comunità. Grazie al loro sviluppo eminentemente sotterraneo, tali opere si sono spesso conservate pressoché intatte per millenni. A partire dall'inizio del Progetto, siamo stati in grado di raccogliere una notevole quantità di materiale documentaristico e di informazioni sugli acquedotti sotterranei, sia mediante esplorazioni dirette negli ambienti ipogei che per mezzo dell'analisi critica della documentazione disponibile. È stata così realizzata una specifica banca dati sugli antichi acquedotti sotterranei in Italia, al fine di salvaguardare queste opere idrauliche di unica importanza storica e idraulica. A tutt'oggi, oltre 140 acquedotti sotterranei, con una distribuzione che copre l'intero territorio italiano, sono stati identificati e oggetto di studio. Oltre agli acquedotti, il Progetto si è anche interessato di ulteriori opera idrauliche, e in

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particolare degli emissari e delle gallerie di drenaggio realizzate a fini di bonifica o per consentire lo sviluppo di pratiche agricole lungo le sponde di bacini endoreici e di laghi. I risultati del Progetto sono stati divulgati mediante numerose presentazioni e partecipazioni a convegni ed iniziative a livello sia nazionale che internazionale, e con la pubblicazione di specifici lavori, ivi compresi due numeri speciali della rivista Opera Ipogea, interamente dedicati alle attività del progetto (nel 2007 e nel 2012). Inoltre, una bibliografia inerente le opere idrauliche sotterranee in Italia è stata costruita, e viene aggiornata di continuo. Essa risulta suddivisa su base regionale e, all'interno di ciascuna regione, con ulteriore suddivisione per ciascuna delle opere idrauliche identificate.

Parole chiave: *cavità artificiali, acquedotti sotterranei, opere idrauliche.*

Introduction

Water has always been fundamental for the birth and development of ancient civilizations, and its availability has played a crucial role in the choice of the sites for new settlements in many periods of the human history. When the hydric resources were not present nearby, they were searched for, and hydraulic engineering works realized, in order to collect and transport them to the inhabited areas. This was generally obtained by means of aqueducts, developed underground (Fig. 1) for most of their length (Castellani & Dragoni, 1990, 1997; Castellani, 1999, 2001).
The oldest form of subterranean aqueducts engineered to collect groundwater is represented by qanats (Fig. 2): this term, which takes its root from a Semitic word

Fig. 1 - Within a branch of the underground aqueduct, dating back to XIX century, at Montecompatri, Latium (photo archive Egeria Centro Ricerche Sotterranee).
Fig. 1 - Uno dei rami dell'acquedotto ottocentesco di Montecompatri, Lazio (foto Archivio Egeria Centro Ricerche Sotterranee).

meaning "to dig", indicates hydraulic works through which the water was collected, and directed by means of a gently sloping underground conduit to surface canals, to provide water to agricultural fields or oases. Qanats represent one of the most ecologically balanced water recovery methods available for arid and semi-arid regions, since do not upset the natural water balance, relying entirely on passive tapping of the water table by gravity. According to archaeological evidences and written accounts, the method of qanat irrigation was first invented in the Armenian-Persian region about 600-700 B.C. (Lightfoot, 1996). The dating, however, is in some way controversial, and some scholars claim the first realizations of qanats has to be brought back to three thousands years ago (Wulff, 1968).
At this regard, it has to be mentioned that the art of tunnelling, as well as the expertise in realizing deep shafts and underground canals to transport water, were probably even older, as testified by the drainage works realized at Kopais, in Boeotia, at the beginning of the 2nd millennium B.C. (Knauss, 1991), or by the attempts of the Mycenaean civilization to cross a mountain ridge with a man-made drainage tunnel discharging the water toward the sea around the 12th century B.C. (Castellani & Dragoni, 1997).
Management in drinking water supply has always been of fundamental importance. The need to having available the necessary amount of hydric resources for the populations pushed ancient populations to tremendous efforts in planning, realizing, and maintaining long and complex aqueducts, that developed underground for most, if not all, of their length. To provide one of the most significant examples for the Italian territory, when the engineer Sextus Julius Frontinus was appointed, in AD 79, as imperial water commissioner *(Curator Aquarum)* of the City of Rome, he became responsible for a supply of 800 megalitres daily into the city from nine underground aqueducts, with a total length of 420 km (Lanciani, 1869; Judson & Kahane, 1963; Bono & Boni, 1996; Pike, 1999).
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. Three main advantages for building the aqueducts underground must be reminded (Assante, 2007; Tassios, 2007): i) to conceal and to protect them from enemies; ii) to protect them from erosion and deterio-

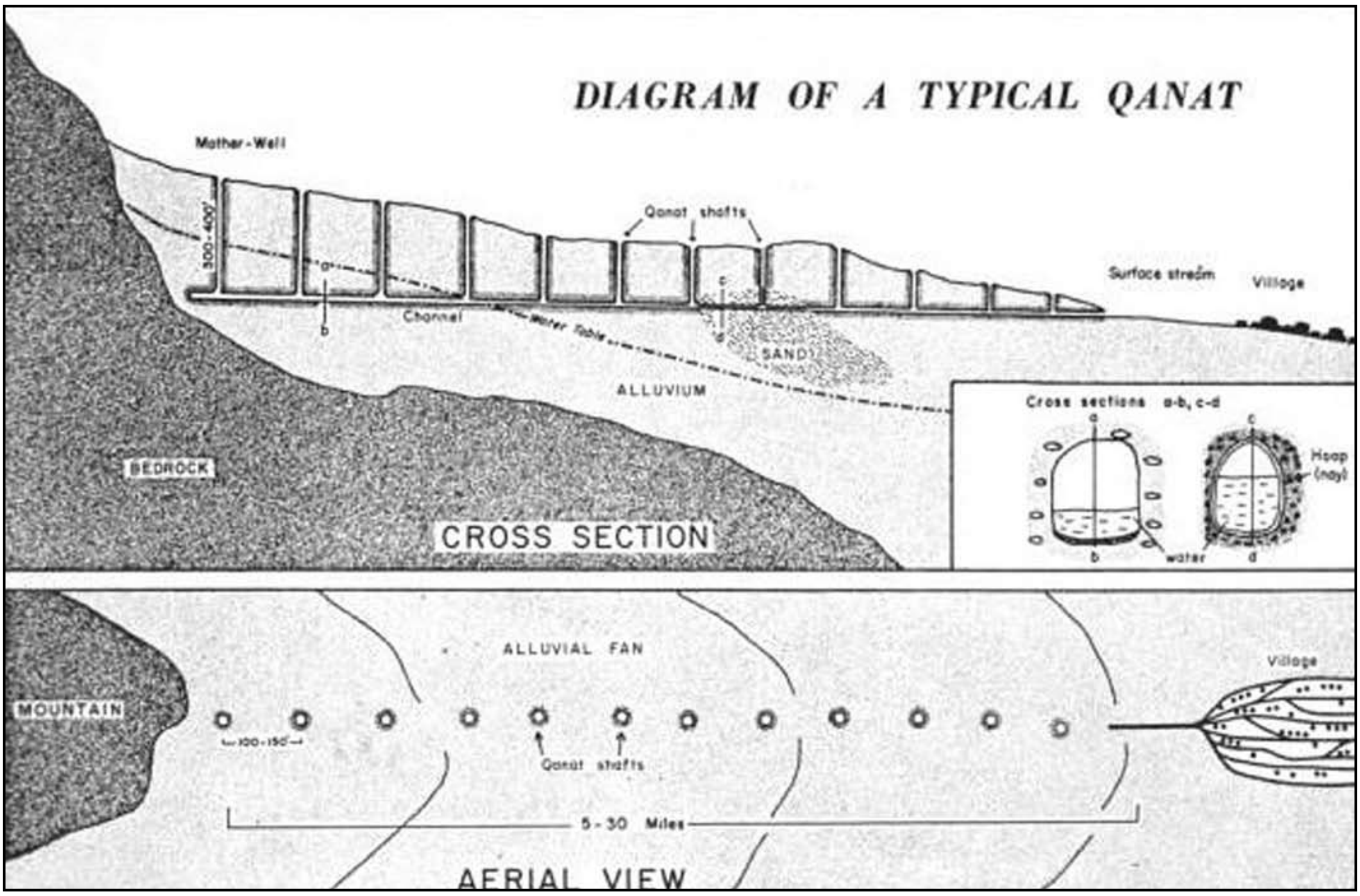

Fig. 2 - Diagram of a typical qanat (after English, 1968). Profile, cross section, and aerial view illustrating the various dimensions of a tunnel-well.
Fig. 2 - Schema di un tipico qanat (da English, 1968): si riportano il profilo, le sezioni trasversali e la vista dall'alto, per illustrare le dimensioni delle gallerie e dei pozzi della struttura idraulica sotterranea.

ration; iii) to be less disruptive to life above ground. On the other hand, the main disadvantage was represented by the greater difficulties in maintaining and inspecting the systems (Castellani, 1999, 2001).
In many cases the final structure was a mostly underground aqueduct, with intervening sections above ground (Fig. 3).

Fig. 3 - Arches of the Claudio Aqueduct at the Aqueducts Park in Rome (photo archive Egeria Centro Ricerche Sotterranee).
Fig. 3 - Il Parco degli Acquedotti: le arcate dell'acquedotto Claudio, Roma (foto Archivio Egeria Centro Ricerche Sotterranee).

As appears from the above considerations, ancient hydraulic works represent a widespread cultural heritage, that locally has become so significant to be a sort of marker of the anthropogenic landscape.

The Project "The Map of Ancient Underground Aqueducts of Italy"

In 2003, the Italian Speleological Society (SSI) started the project "The Map of Ancient Underground Aqueducts of Italy", entirely dedicated to the study and exploration of ancient underground aqueducts and other hydraulic works (Parise et al., 2009; Germani et al., 2009a, b). Ancient aqueducts, together with other subterranean works designed and realized for water collection, transport, and storage (lake outlets, cisterns, tanks, etc.; Fig. 4), have been since a long time explored and studied by cavers. Their importance derives from a number of historical, engineering, and environmental reasons: in fact, they represent a valuable documentation of the skill and engineering techniques of the ancient communities, and are among the main works that testify the efforts by man to manage the territory, and to develop urban civilizations (Tolle Kastenbein, 1990; Laureano, 2009; Parise, 2011). Further, due to the mostly underground development, aqueducts have often been preserved intact for millennia, and in many cases are still working today (Fig. 5), even though lacking

a continuous maintenance. In those situations where problems of instabilities have occurred, aqueducts might be put again at work through low-cost interventions, thus representing additional water supplies in case of droughts or during hydrologic crisis.

The Project involved tens of cavers in many Italian regions, that started new research looking for underground aqueducts or worked in critical analysis of the available documentation and texts, aimed at reconstructing the development of hypogean hydraulic works, and evaluating their actual conditions and state of preservation (Fig. 6). Since the Italian territory presents a huge amount of ancient hydraulic works, two time and space requirements had to be fulfilled to includes an aqueduct in the database (Parise, 2007): 1) the upper time limit of the aqueduct construction is considered to be the XVIII century; 2) the aqueduct must be at least 400 meters long. As regards the latter requirement, however, some exceptions have been made, in case of smaller aqueducts that were of particular importance for some historical, geological or environmental reasons (Fig. 7). As concerns age of the hydraulic structures, the aqueducts have been temporally sub-

Fig. 4 - The roman cistern at the Villa of Consul Quinto Assio (Rieti, Latium). Photo: archive Egeria Centro Ricerche Sotterranee.

Fig. 4 - La cisterna romana della Villa del Console Quinto Assio (Rieti, Lazio). Foto: Archivio Egeria Centro Ricerche Sotterranee.

Fig. 5 - Examples of underground aqueducts: a) ancient aqueduct, re-worked in the XVII century by monks of the Camaldoli Hermitage at Mount Tuscolo (Latium); photo archive Egeria Centro Ricerche Sotterranee; b) branch of the late roman aqueduct at Roccarainola (Campania), realized in pyroclastic deposits; photo F. Maurano; c) channels within the aqueduct Fontana della Stella at Gravina in Puglia (Apulia); photo G. Bologna.

Fig. 5 - Esempi di acquedotti sotterranei: a) acquedotto di epoca arcaica, ristrutturato nel 1600 dai Monaci dell'Eremo di Camaldoli sul Monte Tuscolo (Roma, Lazio); foto Archivio Egeria Centro Ricerche Sotterranee; b) ramo dell'acquedotto tardo romano di Roccarainola (Napoli) scavato in depositi piroclastici; foto F. Maurano; c) canalette per il deflusso dell'acqua all'interno dell'Acquedotto Fontana della Stella a Gravina in Puglia (foto G. Bologna).

Fig. 6 - Covered channel on one side of the gallery at the Montecompatri aqueduct, Latium (photo archive Egeria Centro Ricerche Sotterranee).

Fig. 6 - Acquedotto ottocentesco di Montecompatri (Roma, Lazio). Particolare di canalina ricoperta (foto Archivio Egeria Centro Ricerche Sotterranee).

divided into three periods: i) greek-roman time (until VI century B.C.); ii) byzantine-medioeval time (VII – XIV century B.C.); and iii) renaissance-modern time (XV – XVIII century B.C.).

A specific form was implemented for the project, consisting of three parts (general data, technical data, and personal data) in order to facilitate the collection of the main information about each aqueduct. The general data include all the relevant information about name and location of the aqueduct (region, province, municipality), length (with indication of the percentage of subterranean course), and availability of plan and sections. In addition, the present state of the structure, and the possible necessary works for its re-utilization, are also indicated. Eventually, the general data includes all the bibliographic references dealing with that specific aqueduct. The technical data of the form encompasses information about the geological and hydrological setting of the area where the aqueduct develops, with particular reference to geology of the spring area, and any geological (stratigraphic or tectonic) change along the course of the aqueduct. They also include the known notice about age of utilization of the aqueduct. The personal data, eventually, refer to name, address and correspondence of the form's compiler, in order to have the possibility to contact him/her for further requests.

A very important part of the project consisted in putting together all the references about ancient underground aqueducts, that are often dispersed in many local or sectorial publications, journals or conference proceedings. A thorough work of bibliographical research, and a subsequent phase of cross-checking among the main literary sources, allowed to develop a list of over 1,200 publications (the first release of the bibliography was published in Parise, 2007). These were subdivided on a regional basis, and within each region they were in turn associated to each hydraulic work. The bibliography is continuously being updated.

The number of aqueducts so far inventoried (over 140) is certainly not a definitive one, but expresses the great potentiality of the Italian territory as regards the presence of ancient hydraulic engineering works. Practically all regions of Italy present at least one underground aqueduct (the only exception being Calabria, where so far no ancient underground hydraulic work has been documented). As expected, Latium hosts the great majority of aqueducts, counting 42 hydraulic works, followed by Marche and Campania (13), Apulia (12), and, with smaller numbers, all other regions.

The majority of ancient aqueducts is comprised between 1 and 5 km, but there is a high percentage of aqueducts with a longer course, namely over 10 km (with at least a dozen longer than 30 km). With reference to age of realization of the hydraulic works, over four/fifth of the inventoried aqueducts is of greek-roman age, whilst only one aqueduct has been catalogued as byzantine-medioeval, likely following an older (probably roman) course. The remaining aqueducts are of renaissance-modern time.

However, it is worth making some considerations about age of the aqueducts: in many cases the date of construction often comes from historical sources (for instance, an ancient author indicates explicitly in the text the date of beginning, or end, of the work, together with the emperor's name). In other cases, the age is de-

Fig. 7 - Roman aqueduct at S. Egidio del Monte Albino (Campania; photo S. Del Prete). The picture shows development of calcite deposits in a sector of the hydraulic work dug in fan gravels alternating with pyroclastic deposits.

Fig. 7 - Acquedotto romano di S. Egidio del Monte Albino (Salerno, Campania). Settore concrezionato di acquedotto scavato in alternanze di ghiaie di conoide e depositi piroclastici pedogenizzati (foto S. Del Prete).

rived from the functionality of the aqueduct: for example, it provided the water supply to a roman colony, thus it is a roman aqueduct. In still other situations, dating is just an hypothesis (for instance, it is called roman aqueduct, but actually no documentation which can prove the date is available).

Utilization of the aqueducts was rather diversified: they mostly took drinkable water and transported it to *domus*, *villae*, towns, thermal baths, and military camps (Galeazzi & Germani, 2007). In a few cases, the aqueduct supplied water to mills and factories, by providing the purpose-built wheels with the energy for the production process (Bixio et al., 2007).

There is no uniformity in the geological setting of the source areas of ancient aqueducts. In most of the cases, rocks of sedimentary origin (35%) crop out in the areas where the springs are located. These are followed by carbonate (31%) and volcanic rocks (30%), while a much lower percentage interests debris deposits (4%). The study of the geological setting of the area where the hydraulic works are located, including the difficulties related to the presence of different types of rocks to dig the underground tunnel is a very interesting topic, that is worth to be analysed in greater detail, both as regards the single aqueducts and the overall framework of the territories where these engineering works were realized (Del Prete & Parise, 2007). More in general, it has to be noted that the deep knowledge the ancient populations had about hydrogeology, hydraulics and topography, in order to design, and correctly realize, underground aqueducts, is really astonishing. To obtain the correct functioning of long hydraulic works is definitely not a simple matter; however, the task was reached with precision and working capability, that testify the high level of techniques by the ancient population.

Other hydraulic works

In different geomorphological settings of central Italy (from lakes of volcanic origin, to karst poljes) the local geological, topographical and hydrological conditions made necessary the realization of man-made underground passages to reclaim land (Fig. 8) or to regulate the permanent and/or temporary water levels (Caputo et al., 1974; Dragoni, 1982; Faccenna et al., 1993).

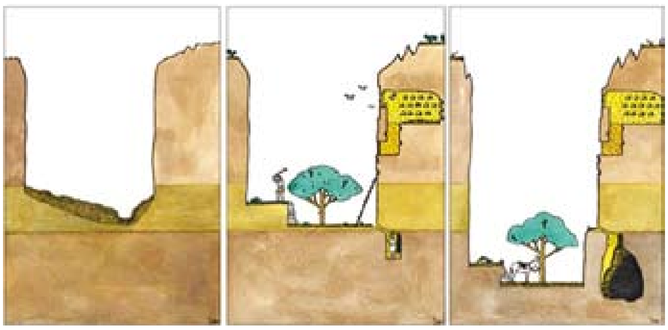

Fig. 8 - Sketch of construction of a drainage tunnel for land reclamation (drawing R. Bixio).

Fig. 8 - Schema di realizzazione di un canale di drenaggio sotterraneo per opera di bonifica (grafica R. Bixio).

These hydraulic works were planned and realized for several aims that included, but were not limited to, agricultural practices and collection, transport and distribution of water to human settlements (Germani & Parise, 2010).

Etrurians and Romans, in particular, dug long underground galleries to reclaim many closed basins between VI century B.C. and II century A.C. (Castellani & Dragoni, 1989; Burri & Petitta, 1996).

Identification and study of the artificial drainage tunnels of volcanic lakes and karst poljes was the natural corollary of the first phases of the project “The Map of Ancient Underground Aqueducts”. To this typology of hydraulic works, an issue of Opera Ipogea has been almost entirely dedicated (see Galeazzi et al., 2012). The preliminary list of the hydraulic works identified so far include 12 drainage tunnels in Latium, 4 in Tuscany, 3 in Umbria and 1 in Abruzzo.

Underground drainage tunnels were realized to control the water levels of permanent or temporary lakes and basins. These works were planned in order to allow agricultural practices along the shores of the lakes, or as water supply tunnels to provide with drinkable water human settlements (De La Blanchere, 1882; Del Pelo Pardi, 1943). Apart from these goals, the control of the water levels of lakes was also used to provide energy for mills and other working sites.

In the time span between the VI century B.C. and the II A.C., Etruscans and Romans became masters of these engineering works, and were able to drain several basins. Among the most interesting examples, it is worth to remember the drainage tunnels at the Lake of Nemi, in Latium (VI century B.C., 1650 m of length, absence of shafts along the tunnel) and of Fucino (I century A.C., length about 6 Km; Brisse & De Routrou, 1876; Burri, 1994). At Nemi, a very complex system of tunnels and artificial conduits allowed control and irrigation of the fields (Ucelli, 1954; Caloi & Castellani, 1991; Castellani, 1999; Castellani et al., 2002, 2003; Dobosz et al., 2003; Drusiani, 2003; Medici, 2005; Galeazzi & Germani, 2007), beside including also two mills (Giannini, 2006). Further sites of interests for drainage tunnels are the Albani Hills, in Latium (Dolci, 1958; Cardinale et al., 1978; Caloi et al., 1994), and the Trasimeno Lake in Umbria (Frosini, 1958; Castellani & Dragoni, 1981; Burzigotti et al., 2003).

Conclusions

The Project is still in progress, and can actually be considered as an on going process. The amount of sites to study, and where to collect further data, is actually enormous in a country as Italy. The efforts by the Italian Speleological Society (Fig. 9) have necessarily to be strictly linked to research centres and universities, in order to have the possibility to give continuity to the project and keep working on this subject.

Studying ancient underground aqueducts (or, more in general, hydraulic works) represents an exciting challenge, that may open new lights toward the capability of man to collect water in the past and, more generally,

Fig. 9 - Two images in the underground aqueducts at Montecompatri, Latium (photos: archive Egeria Centro Ricerche Sotterranee).

Fig. 9 - Due immagini all'interno di acquedotti sotterranei nel territorio di Montecompatri (Roma, Lazio). Foto Archivio Egeria Centro Ricerche Sotterranee.

to work toward a sustainable use of the natural resources (LAUREANO, 1995; BURRI, 2002; PARISE, 2011). On the other hand, the periodic hydrologic crises we experience, often related to over-exploitation and degradation of the water resources, demonstrate that several lessons may be learned from the analysis of ancient hydraulic works (CASTELLANI & DRAGONI, 1991; PARISE et al., 2012).

Aimed at further co-operations with foreign scholars and cavers, a systematic research about bibliographic references to ancient underground aqueducts outside of Italy was also started, and the first contributions in this sense published (PARISE, 2012).

The interest on the topic is in fact great even outside the Italian boundaries, and especially in the other countries of the Mediterranean Basin, where many other important ancient hydraulic engineering works have been built and used during the different epochs. At the time we write (December 2012) a list of some hundreds of bibliographical references about underground aqueducts distributed all over the world has been compiled.

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