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Water Management Structures in Historical Settlements: Towards a Cross-Geographical, Cross-Cultural Categorization

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Abstract In almost all the studied historical settlements place and water in its most general, both symbolic and practical definition, appear to be interwoven and interdependent. There are many references regarding the construction methods, shape and usage of water management structures in historical settlements. However, little research has been conducted comparing the findings of water structures to one another. In this paper a categorization of significant existing water management structures in historical settlements is attempted on the basis of their main function and role in the water exploitation process. *Collection*, *Transportation* and *Storage*, as well as combinations of the above, have been identified as the main categories of water management structures in historical settlements. Examples of structures belonging to each category that come from various cultural backgrounds and geographical areas are discussed and a further categorization of structures belonging to the same category, based on ground/structure relationship, is also attempted and presented in the paper.

Keywords: water collection; water transportation; water storage; categorization;

INTRODUCTION & BACKGROUND

Water constitutes a part and parcel of a place's evolution and cultural history. In all historical settlements, place and water in its many facets appear to be interwoven and interdependent, a fact that explains the strong presence of water in both the cultural customs of every place and the measures that ensured humans' survival in it. With the same token, the technologies and structures that are pertinent to water exploitation in a specific place are closely related to its inhabitation and hence to its land formation and the natural resources in the area. Although "why" water has determined the place in the map of a settlement is self-explanatory, the manner in which historical settlements were related to water, or more specifically how historical settlements utilized their water resources, is not always as obvious. It is thus interesting to shed more light on the followed steps in the water management process and on the structures that were used for transferring the water from the location it was found till the final location of its consumption.

Significant findings on historical water structures have been reported in bibliographic references. The majority of these references address the water structures' shape (Angelakis et al., 2012,) and documentation (Antoniou, 2006; 2009; Bonde et al., 2012; Fonder et al., 2006; Halemane, 2007; Ortloff, 2005; Vojdani et al, 2012; Fotiadou et al, 2012; Dahlin et al., 1986), while others discuss the material properties and the technical features of historical water structures (Guida et al., 2008; Fathy, 1976; Tassios, 2006). Also, many publications address cultural aspects (Saitas, 2001; French, 2002), and the evolution in time of certain prototypical structures (De Feo, 2006; Farhangi, 2007; French, 2009; Mays, 2012; Ward, 2012). A smaller number focuses on water management issues (Koutsoyiannis, 2012; Laureano, 2006; Showleh, 2006), while others place emphasis on the exploitation of water resources (Kogan et al., 2002; Khaleq, 2006; Parise, 2012; Beysens et al., 2000; Batina et al., 2013). These studies are mostly based on findings that come from places with mostly the same cultural context and from a limited range of geographical locations.

This paper departing from a cross geographical, cross cultural collection and overview of water structures, attempts a categorization of water management structures in historical settlements. With this objective in mind, the findings reported in literature have been compared according to the function of the structures in the water management and exploitation sequence. Out of this comparison three (3) main categories of water management structures were identified: 1) *Collection*, 2) *Transportation*, and 3) *Storage*, that are described in the following sections.

WATER COLLECTION STRUCTURES

Water collection is the stage in the water exploitation sequence that precedes all other stages of water management, according to the proposed categorization in this paper. Hence for this study, water collection structures consist a category on their own. Comparing water collection structures to each other has indicated that existing structures can be further categorized on the basis of selected characteristics.

An important observation encountered in some references is that the water in the collection stage was not always in liquid state, but it could also be gaseous. As the phase of water depended on the relationship of the water collection structure to the ground, a further classification on the relation of the water collection structures to the ground has been suggested. Thus, the collection structures, in this paper (Fig. 1.I.), are organized in structures for the collection of: a) *Rainwater*, b) *Water vapor*, c) *Surface water*, and d) *Underground water*. Structures that serve principally for collection are discussed below.

Collection of rainwater (Fig.1.I.a) was encountered usually in areas where the precipitation levels could be as much as 400 mm. per year. Collection of rainwater was then part of water management systems that also include transportation and storage. Such structures provided water for irrigation, house-cleaning, and, in some cases, the water was purified in order to be used as potable water.

Collection of water vapor (Fig.1.I.b) instead is encountered in arid regions with significant humidity (Beysens et al., 2000). The main purpose of water vapor collection structures was to condense air humidity into clean water. At the beginning of the 20th century many researchers have tried to invent methods to utilize this promising hidden water resource. The result was the creation of *air wells*, structures that managed to condense vapor in order to collect liquid water. These structures were of high mass so that during the day, the material of the structure absorbed heat and during the night the heat was released by radiation, having as a result the condensation of the water vapor adjacent to it. However, this type of air-wells was found not efficient enough since they could not liquefy a significant amount of vapor (Batina et al., 2013). Despite that, air-wells have motivated contemporary researchers who have designed air-well structures with more efficient results.

Collection of surface water (Fig.1.I.c) refers to a way of diverting or retaining an amount of the water in rivers and lakes. Collection of surface water was made possible either through the erection of low and thin walls next to springs in order to lead the water to specific directions, or via large dams with high and thick walls that retained large amounts of water from flowing into the sea. We seldom encounter large scale dams in historical settlements; these mostly appear after the second half of the 20th century since they require specialized engineering; the Aswan dam, Egypt, built in the 1960s is one of them.

Collection of underground water (Fig.1.I.d) was the most common method of providing water to a historical settlement and was achieved through *wells* since the 75th century B.C. Early examples of wells are found in Cyprus. Despite their common use, their construction was not always possible, since they required aquifers with clean water, as well as significant man power.

These four subcategories were combined with water transportation and/or water storage structures in all instances of studied examples, so specific historical examples are presented only in combination with water transportation and storage structures.

WATER TRANSRPORTATION STRUCTURES

Almost in all cases of water management structures transportation of water followed the stage of water collection in a settlement. Transportation structures present differences that mostly relate to their relationship to the ground. Accordingly, in this research, water transportation structures have been divided into three subcategories (Fig.1.II): a) *Above ground*, b) *Surface*, and c) *Underground* structures.

The most simple category of water transportation structures are the surface ones since they required the minimum manpower for construction. The *Hellenistic aqueducts* (Fig.1.II.a) are probably the most significant example of *surface* water transportation structures since they utilized the natural flow of water in rivers, and controlled the water flow by directing the water inside closed conduits and exploiting the “communicating vessels” principle. The Hellenistic aqueducts were usually very long and, eventually, expanded outside the settlements they served. In some instances their size was up to 40km long. In areas with rough topography, with hilly areas followed by flat planes the size of the conduits over the valleys had to be much longer compared to their size over the planes.

The *inverted siphon* (Fig.1.II.b), a Greek invention that provided a solution to such situations, is a type of structures of above ground water transportation that is often encountered in the findings of this category of structures. In this structure the conduits were of closed section and, based on the “communicating vessels” principle, could lead the water to the opposite hills with conduits of less length (Fonder et al., 2006).

A prominent example of water transportation structures combining *underground, surface and above ground* transportation methods were the *Roman aqueducts* (Fig.1.II.c). These were more complex water transportation structures that were not throughout their length detached from the ground and supported by repeated arcs as many believe. Instead, depending on the topography, where it was necessary, water bridges, sedimentation tanks, underground tunnels with vertical shafts and inverted siphons were constructed.

Underground transportation is the second subcategory of water transportation. Typical example of *underground* transportation is the *Eupalinian tunnel* (Fig.1.II.d) in ancient Samos, Greece, constructed by the engineer Eupalinos circa 530 B.C. This was an entirely underground structure, crossing a mountain, dug out without any intermediate vertical shafts (De Feo et al., 2006).

The mentioned ground structures supported the transportation of water on a flat or a sloped surface. However, *vertical underground* water transportation is also found in particular cases like in *Cappadocia's underground cities* (Fig.1.II.e). These underground settlements were constructed under existing cities to provide shelter for the population from raids. A prominent example of such a settlement is the underground city of Derinkuyu. This consisted of eleven underground levels with vertical shafts that functioned either as wells or as air shafts for ventilation. Some of the wells of this settlement unlike common wells could be accessible from underground levels, while other wells didn't communicate with the surface in order to protect the water resources from poisoning by enemies.

WATER STORAGE STRUCTURES

Water transportation in most cases is followed by water storage structures. Water storage structures were very important in regions with dry climate where people's survival couldn't depend only on rainfall. An overview of the findings of this category has shown that their relation to the ground is very important (Fig.1.III.). Thus, in this paper water storage structures have been classified into: a) *Carved*, when cavities are created to retain water, and b) *Underground* structures, cisterns or tanks, entirely carved inside the ground with small openings to the surface.

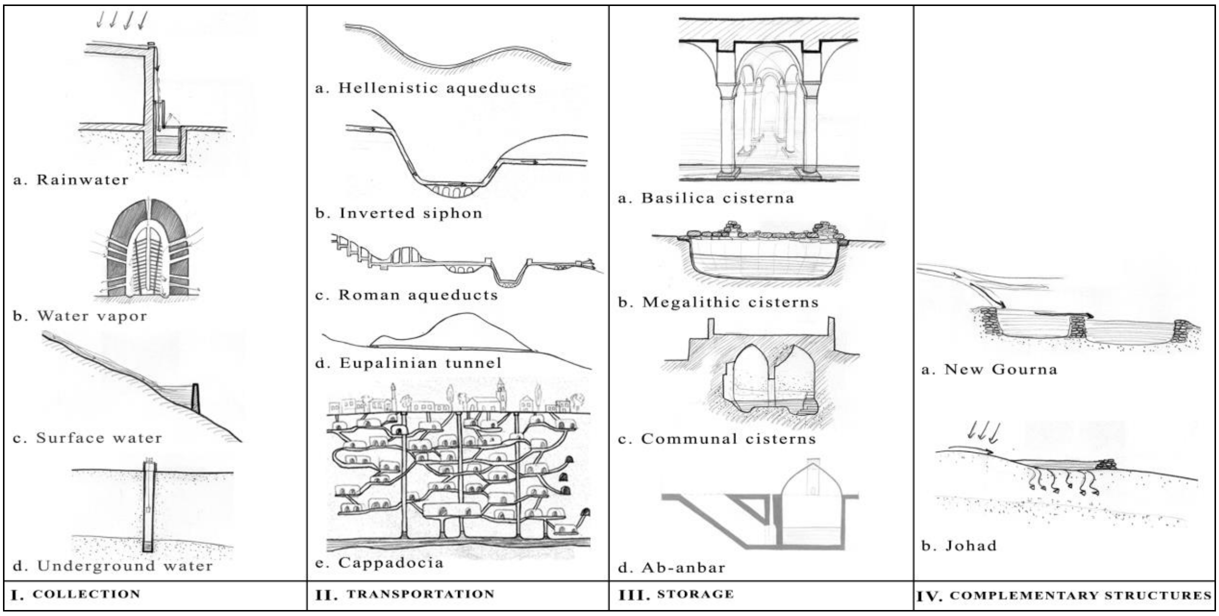
The findings have also indicated that carved cisterns can be divided into: i) open, and ii) covered, where the water is protected from weather and pollution. Interesting enough is the fact that no above ground storage structures were encountered in the findings, probably due to the fact that their construction might have been extremely difficult, as well as the process to render them watertight.

A renowned example of underground storage was *Basilica cisterna* (Fig.1.III.a), the largest remaining byzantine cistern out of hundreds constructed under Istanbul, Turkey. One of the greatest water storage structures, Basilica Cisterna satisfied the Great Palace's needs in water during the summer, when alternative water resources were depleted. It was covered with light vaulting and its colonnades remind those of significant temples. The water's surface reflects the whole structure, creating a unique ambiance.

A significant example of covered carved water storage structures, with smaller size than Basilica Cisterna, consist the *megalithic cisterns* (large-rock cisterns) in Mani, Greece (Fig.1.III.b). Due to the ground of the area, the locals constructed the cisterns out of the available large rocks which were abundant. Thus, they were able to bridge large gaps to cover the cisterns. These cisterns were carved out of the soil and were found in the backyards and the public spaces of the small communities of Mani.

Another characteristic example of *carved* water storage structures are the <u>communal cisterns</u> on the island of <u>*Amorgos*</u>, Greece (Fig.1.III.c). There, people chose to overcome water shortage as a community. This was achieved with the construction of cisterns for the whole settlement, not only for each residence. Remnants of these ancient cisterns are found at the main settlement's outskirts (Antoniou, 2009). Once they were unroofed but later on they got *covered* with vaults during the Byzantine period. The water storage structure was accessible either from openings on their roof or with stairwells that led down to the cistern.

Another important instance of covered carved storage structures are the <u>*ab-anbars*</u> (Fig.1.III.c) in Iran. Ab-anbars stored water from precipitation and underground aquifers. They were covered with vaults to minimize loss due to evaporation. Besides, they provided cool water during hot summer months and were usually combined with windcatchers for cooling through evaporation. They also had a carved stairwell attached for access to the water.



1.I **1.II** **1.III** **1.IV**

Figure 1 Water Collection, Transportation, Storage and Complementary Structures: Sections

COMPLEMENTARY WATER STRUCTURES

Among the studied cases we identified structures, the main role of which was to complement the water management sequence. The most important complementary roles of these structures were for *water sanitation* and *groundwater recharge*.

A characteristic historical water structure in this category that served for water sanitation was found in the village <u>*New Gourna*</u>, Egypt (Fig.1.IV.a). The architect Hassan Fathy managed to provide potable water to the inhabitants, by cleaning it from the parasites that had contaminated Nile's water causing bilharzia (Fathy, 1976). Diverting an amount of water from the river through canals and storing it in an artificial lake he cleaned only the stored amount (Fig. 1.IV.a). It is worth mentioning that the sides of the lake were covered with stones to prevent plants, which would feed parasites, from growing. Accordingly, water was kept in a clean tank for two days and, then, it was safe to drink.

Groundwater recharge was another sub-category of complementary structures. This role of water structures was encountered in cases like *johad* in Rajasthan, India. Johad was used for collecting rainwater and directing it to the local aquifer. This structure, (Fig. 1.IV.b), consisted of a semicircular dam made of stones, soil and clay, that retained rainwater. Retaining the water, johad enabled it to be absorbed from the ground and replenish the aquifer. Thus, water could be stored underground without cisterns.

WATER COLLECTION AND TRANSPORTATION STRUCTURES

In our effort to categorize water management structures we found structures that combined the stages of both water collection and water transportation. These structures are presented below.

A known example of water collection and transportation structures was found in *Machu Picchu*, Peru (Fig. 2.I.a). This type of water structure provided abundant water, even for the dry season, so water storage was not necessary. In Machu Picchu water was collected from springs through a small dam and was then transported along a wall and a canal. Due to the difference in altitude between the settlement and the springs, water descended from the mountain through terraces, irrigated the cultivations and reached the settlement. Water was then accessible to the inhabitants through fountains, the first of which had to be the emperor's fountain. In this way, the topography of the region and the design of the canal determined the masterplan of the settlement.

Another characteristic example in this category was the *qanat* (Fig. 2.I.b). The qanat is one of the most significant methods used to provide water in arid regions around the world. It was invented in Iran 3 millenia ago in areas with mountains in order to extract underground water. Qanats were rarely built individually; they were usually constructed in groups with branches so that they could direct water to several points at the foothills. The advantages of this method were the decrease in water loss due to evaporation and the absence of pumping system unlike common vertical wells, since water flowed due to gravity. However, they presented a strong disadvantage regarding the depletion of the local aquifers, when not used prudently.

A more simple version of the qanat was encountered in the *suranga*, a structure encountered in the southwest part of India. This method (Fig. 2.I.c) functioned in the same way qanats did, collecting water through percolation and transporting it through a sloped underground canal. However due to the hard local surface rock, digging vertical shafts was extremely difficult. Because of that the underground canal was relatively small in length (40 m. long instead of 120km. for a qanat).

WATER COLLECTION & STORAGE STRUCTURES

Some of the studied cases served for water collection and water storage instead of water collection and transportation. A characteristic example of water collection and storage structures present the *drystone walls* (or specchie) (Fig. 2.II.a). These were mostly encountered in the Sahara Desert and some Mediterranean countries like Italy and Spain (Laureano, 2006). These structures consisted of a tank, carved inside the ground and covered with a small dome-like drystone structure. Due to the difference between the temperature of the surroundings and that of the inside of the structure (Parise et al., 2012) water vapor condensed and flowed, as liquid water, to the enclosed tank. This method could provide only limited amount of water.

Another significant example of this type of structure present the *kunds* (Fig. 2.II.b), encountered in India. These structures, also carved inside the ground, had a similar shape to the drystone walls but collected rainwater instead of condensed water vapor. To protect water from atmospheric heat they were covered with a vaulted ceiling and had small openings for the entrance of water. The users had access to the stored water through a larger opening on the top of the roof. The kunds were constructed on sloppy surfaces in order to minimize the amount of rainwater absorbed from the ground.

The *stepwells* of India present another important case of water collection and storage structures. Stepwells appearing from 550 B.C and on, (Fig. 2.II.c), were open cisterns of diverse dimensions that could provide water even for large communities They collected rainwater during the monsoons and stored it for use during the dry season. Stepwells, as one can understand from their name, consisted of the main vertical shaft, the well, and the steps leading to its bottom. Most stepwells were complex and ornamented, combining their use with entertainment due to the mild microclimate caused by the evaporative cooling effect.

The simplest type of collecting and storing water is the natural *pond* (Fig. 2.II.d). This is an open tank collecting rainwater from declivities adjacent to it. The pond water was utilized only for crops and flocks since no clean water or purification was provided.

A more complex structure than the pond, *souvala* (or *mpourdechtis*), was encountered in the island of Aegina, Greece (Antoniou 2006). A souvala (Fig. 2.II.e) was an open carved cistern for the collection and storage of both underground and rain water, for year-round. Souvala was usually located at the highlands of the island and references to it date back to the Hellenistic period. Depending on the location of each cistern with regard to the ground, souvala could be partly carved combining natural cavities with stonewalls, like a dam reminding a johad (Antoniou 2006). Most of the souvales were found next to the regions they provided water for; so there was no need for water transportation.

Another significant instance of this type of structures are the Mayan *chultuns* in Central America (Fig. 2.II.f). Chultuns were underground cisterns that, like stepwells, collected rainwater during the rainy season, and had declivities around them to direct water in the cistern, like kunds and souvales. In order to serve as the main water resource in the area year-round, they were usually large, with some of them reaching the capacity of 75.000 lt. Due to the hard surface soil and abundant vegetation these large cisterns were mostly dug underground unlike the open stepwells.

WATER COLLECTION, TRANSRPORTATION & STORAGE STRUCTURES

The last category of the studied water management structures contains those that combine all of the three stages, water collection, transportation and storage.

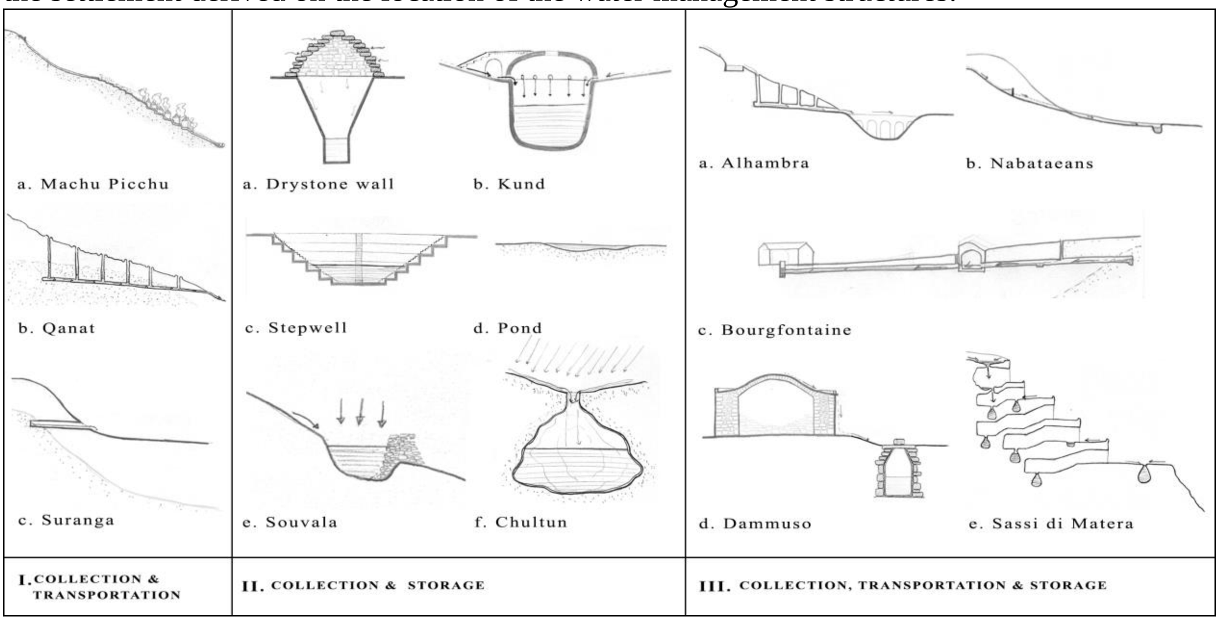
The most renowned example in this category are the water structures of *Alhambra*, Spain (Fig. 2.III.a), that date back to 1238 A.D. Water in Alhambra was collected in the mountain and transported through natural slopes, qanats and aqueducts always exploiting the region’s topography. Water was then either stored for house-hold use, or flowed inside atriums cooling the air with evaporation.

Another significant example of structures combining all three functions, were the water structures of the *Nabataeans* (Fig. 2.III.b), a nomadic tribe of merchants in the Arab peninsula. These structures, significantly larger than its counterpart structures in Alhambra, were located in the desert, and addressed successfully the lack of water resources in the area. By constructing dams in the highlands, adequate amounts of water coming from the scarce rainfalls, was retained and stored in tanks. The quantity of stored water could cover the tribes' needs throughout the year. This water supply system was kept hidden so that only the *Nabataeans* knew the location of the water storage tanks. In this way the *Nabataeans* were able to dominate the desert for half a millennium.

A less known but important structure of this type is the cloister of *Bourgfontaine* in France (Fig. 2.III.c) dating back to the 14th century A.D. This structure, one of the few surviving in medieval France, had one of the longest underground aqueducts of this period that, because of the topography of the area, functioned as an inverted siphon. The storage tank was one of the largest known in medieval France; most of the others had 1/5 of its capacity.

Another example of combined water collection, transportation and storage is encountered in a typical agricultural structure, the *dammuso* (Fig. 2.III.d) in Sicily, Italy. This, relatively small structure, dating back to the 10th century B.C., presented a complete rainwater collection system. Its shape, covered with vaults, funneled rainwater into an underground cistern (Campanelli, 2008).

Another characteristic example of the complete water management sequence is found at *Sassi di Matera*, Italy (Fig. 2.III.e). This is one of the very few known systems of interconnected cisterns and canals. Water from rainfall, percolation and water vapor flowed in this complex water management system (Laureano, 2006). Each of these cisterns retained a specific amount of water and led the rest to the next cistern, providing in this way water for the entire settlement (Parise et al., 2012). This water supply system combined vertical underground structures as well as underground and surface transportation structures. The morphology of the settlement derived on the location of the water management structures.



2.I 2.II 2.III

Figure 2 Water Structures Combining Collection, Transportation and/or Storage: Sections

RESULTS AND CONCLUSIONS

In this study a wide variety of references on historical water management structures was gathered and studied, shedding light on water management processes in historical settlements. The identified differences and similarities of the studied water structures led to the categorization of such structures according to their role in the water management process. It was found that the water management process involved three separate stages: water collection, transportation and storage.

Despite the fact that exceptions to the three categories do exist, like the complementary structures, most of the historical water structures coming from various geographical locations and cultural context fall into one or more of the discussed categories. A comparison between the structures belonging to each one of the three main categories indicated a further categorization according to their placement in relation to the ground.

This cross geographical, cross cultural study revealed important information on the role and succession of structures that play an important role in the water management in historical settlements. As the knowledge gained on water management structures is based on individual findings, further research is needed to provide a better understanding of the complete water management processes in historical settlements.

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