Water supply system of Diocletian's palace ın Split - Croatia

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Abstract
Roman water supply buildings are a good example for exploring the needs and development of infrastructure necessary for sustainable living in urban areas. Studying and reconstructing historical systems contributes not only to the preservation of historical buildings and development of tourism but also to the culture of living and development of hydrotechnical profession. This paper presents the water supply system of Diocletian's Palace in Split. It describes the 9.5 km long Roman aqueduct, built at the turn of 3rd century AD. It was thoroughly reconstructed in the late 19th century and is still used for water supply of the city of Split. The fact that the structure was built 17 centuries ago and is still technologically acceptable for water supply, speaks of the high level of engineering knowledge of Roman builders**.** In the presentation of this structure this paper not only departs from its historical features, but also strives to present its technological features and the possible construction technology. The objective is to emphasize the importance of this structure for understanding of the development of Roman water supply systems and the need for further research and analysis.

Key words: Diocletian's Palace, Jadro spring, Roman aqueduct, Split, Water supply

Introduction

In 305 AD the Roman emperor Diocletian left his throne in Nicomedia (modern Ismit, Turkey) and went to his homeland in order to spend the rest of the life in his palace built in the bay 5 km from Salona, the capital of the Roman province Dalmatia, Fig 1. After his death in 316, the Palace became imperial property and life continued there. In the 7th century refugees from the destroyed town of Salona found shelter inside the Palace, defending themselves from the invading barbarians. There they built new houses and started to live, work and trade. The settling of the Palace by common people is considered the beginning of the City of Split. The city gradually spread around the Palace so that by the 15th century it doubled its surface. Until today it has constantly been inhabited, bearing the features of a common Mediterranean town. Split is now a major city of the Split-Dalmatia County and the second largest city in Croatia. Thanks to the well preserved Diocletian's Palace and buildings of all historical periods, it holds an outstanding place in

the Mediterranean, European and world heritage. In 1979 Diocletian's Palace, together with the historical core of Split, was inscribed in the UNESCO World Cultural Heritage list.

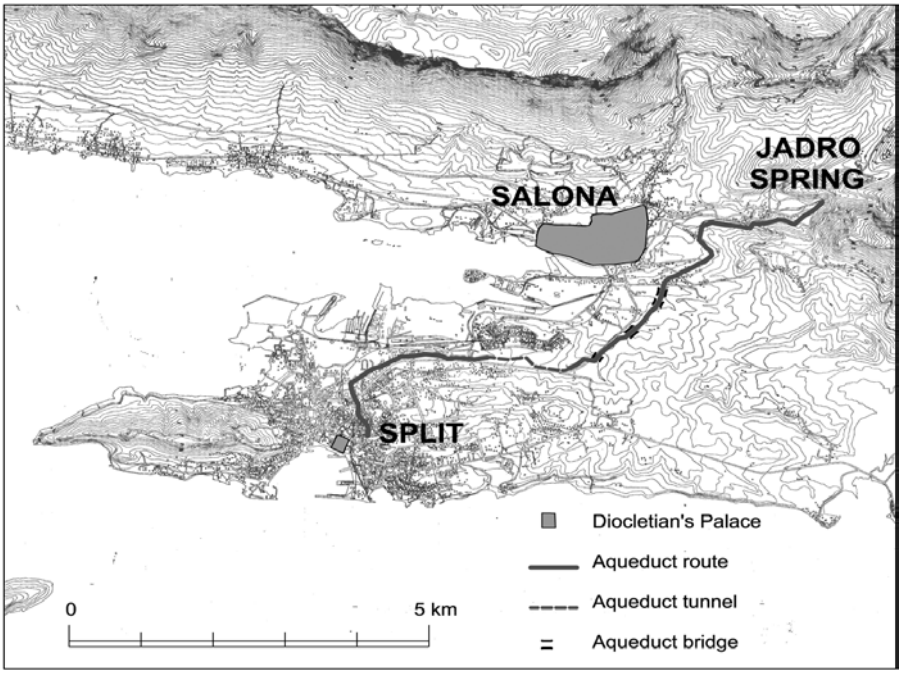

Figure 1. Aqueduct route (Authors)

The Palace lies in a small bay on the Dalmatian coast, on the south side of the Split peninsula. It was built inside the older Roman settlement Spalato dating from the 1st century AD. The shape of the Palace is a rectangle, approximately 180 x 220 meters, Fig 2. Diocletian's Palace combines the elements of a *villa maritima* and a military camp (*castrum*). The luxurious residence, where the Emperor's family lived, was situated in the southern part while the service area, housing soldiers, servants and other facilities, was in the northern part of the Palace. The main square, the so-called "Peristyle" with adjacent religious buildings was in the middle. The Palace possessed all the necessary infrastructure required for living. Thus, among other things, a water system, or water supply and sewerage system were built. The water supply system of Diocletian's Palace will be described in this paper.

The water supply system of Diocletian's Palace used water from the Jadro river spring, Fig 1. In his writings, about 950, Emperor *Constantine Porphyrogenitus* praises this water and states that those who have tasted it say that it is the most delicious of all water (Bulić 1923). The Jadro spring is a karst spring of high capacity and good water quality. The water is still used for drinking without treatment.

The spring is situated on the slopes of the Mosor mountain, 7 km northeast of Split. This spring supplied not only the Palace, but also Salona. That was certainly one of the

reasons that in its vicinity Salona should arise, named after the river Jadro (Salon), Fig 1. The city was supplied with water by a 4 km long aqueduct (Katić 1999). It ceased to function in the 7th century when the Barbarians destroyed Salona which never recovered again. The object of this work is only the aqueduct of Diocletian's Palace.

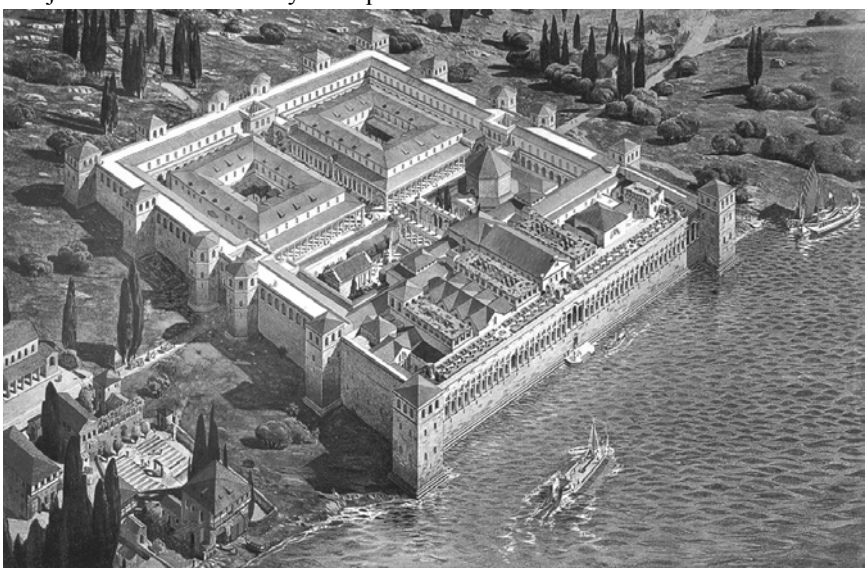

Figure 2. Diocletian's Palace (Hébrard, Zeiller 1912)

Diocletian's palace Aqueduct

The Diocletian's aqueduct was built at the turn of 3rd century AD, simultaneous with the Palace. A unique feature of this structure is that this aqueduct is still in function, so that the water supply of the city of Split, the second largest city in Croatia, is based on the same water supply concept as Diocletian's palace.

In order to allow gravity flow of water from the Jadro spring to the Palace a 9.5 km long aqueduct had to be built, Fig 1. It was in continuous function until the 7th century, when it was destroyed by Avars. At the end of the 19th century the Roman aqueduct was reconstructed and used for water supply of Split, (Bulić, Karaman 1927; Kečkemet 1993). Therefore, a great part of the original aqueduct is preserved and is still in function, which gives us the opportunity to study it and analyze the water supply engineering and technology.

The initial elevation of the channel at the Jadro spring is 33 m above sea level and the end of the channel is some 250 m from the Palace in the *Castellum Divisorium* (dispensing structure) 20 m above sea level. Longitudinal slope of the channel ranges from 0.65 to 2.66 $^{0}/_{00}$, Fig. 4. The dimension of the flowing part of the channel is 60/120 cm (approx 2/4 of a Roman foot), Fig. 5. According to the hydraulic calculation, the channel capacity in ancient times was 715 l/s, whereas today it is 470 l/s, somewhat less than one third of the total water supply in the whole Split area with a total of 300,000 inhabitants, (Marasović et al. 2007). The reason of reduced capacity are water losses as a result of

inadequate maintenance, or non implementation of rehabilitation which is very expensive, because it is a protected cultural monument.

Water intake and ıntake structure

The Jadro spring is a typical karst, cave type water spring of extremely variable capacity, with minimum flow of 3.5 m^3/s during summer, and maximum of about 60 m^3/s during winter periods of heavy rain (Bonacci 2012). The water quality is good, although with increased turbidity in a very rainy period. The spring's elevation allows gravity flow of water to the ancient coastal cities and even today to the centre of Split, where water is pressurized through pumping stations into the water supply system and water tanks.

The original Roman water intake structure on the Jadro spring is not preserved, and therefore it can't be reliably reconstructed. The key factor that defines the possible appearance of the intake structure is elevation of the intake, i.e. hydraulic pressure and intake capacity. Water intake in the spring cave itself allowed to obtain maximum inlet water pressure, but not high capacity. The dimension of the spring cave is about 3x2 m, due to which, construction of any water intake partition in the cave would significantly reduce the flow orifice, therefore large flows would probably destroy such structures. Therefore it is most likely that the original concept is the same one now used for water intake, which is the construction of flow reservoir/lake directly beneath the spring cave. This solution ensures constant pressure and continuous intake of large quantities of water without disrupting the discharge regime from the spring. Water pours out of the cave into the reservoir which has a maximum elevation of approximately 0.5 m below the bottom of the cave. Water is abstracted from the reservoir and excess water spills over the dam into the Jadro riverbed.

Figure 3. Jadro river spring (Bartulović T.)

The intake structure of the Salona water supply was at approximately 20 m above sea level, therefore 13 meters lower than the intake structure of the Diocletian aqueduct. This information was obtained from the level of the preserved channel over the city gate of ancient Salona, the so-called Porta Caesarea, located at an approximate elevation of 15 meters above sea. If the length of the route is 4 km and the channel slope is $1.3^{0}/_{00}$ (average channel slope of Palace aqueduct), a height difference is about 5 meters. At the bottom of the Jadro spring reservoir huge stone blocks can be seen, whose study could provide more precise information about the possible appearance of the Salona Roman aqueduct and intake structure. Research for the purpose of reconstruction of the water intake has been planned.

Aqueduct route and structures

To ensure a continuous slope toward the Palace, it was necessary to build a channel on the ground, below the ground, cuts, tunnels and bridges, Fig 4. Therefore, this structure is a good example of various designs of water supply channels in Roman times. The length of the channel on the ground is about 7100 m, in the tunnel it is 1700 m, on the bridges, 600 m and 100 m in the cut. When architect Vicko Andric researched and documented the structure at the end of the 19th century, he concluded that the ancient aqueduct designer chose the best possible route to ensure the required water pressure in the Palace on the basis of available hydraulic pressure / elevation of the bottom of the cave at the spring, and technological requirements related to potable water quality (protection against pollution, thermal insulation, waterproofing).

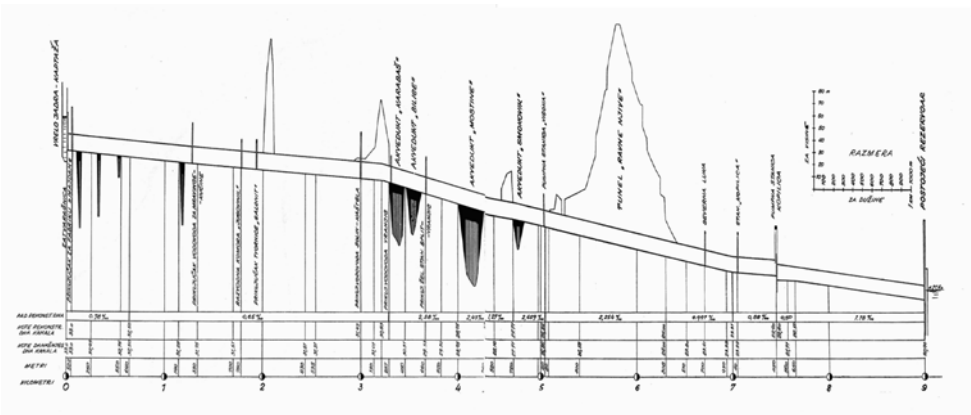

Figure 4. Longitudinal section of the aqueduct route (Katanić, Gojković 1972)

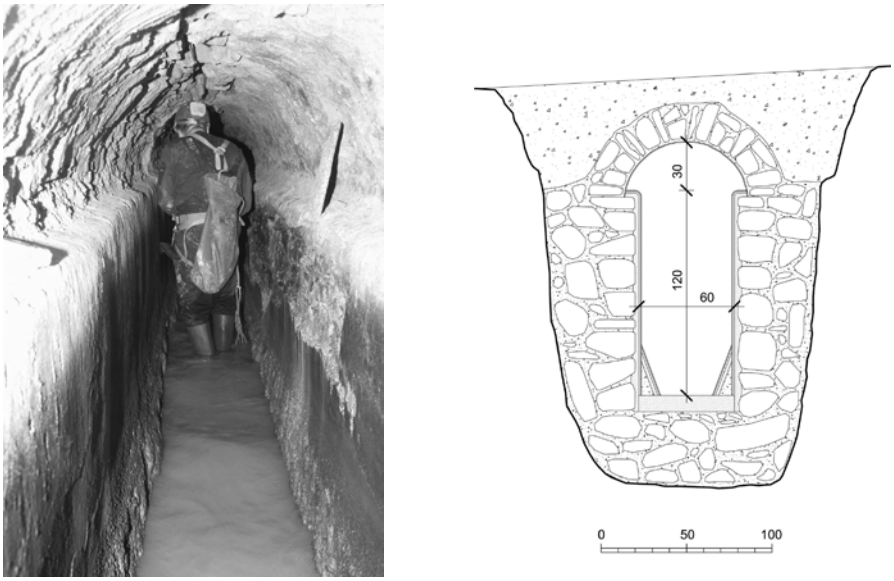

Figure 5. The Diocletian's aqueduct channel (photo: Bartulović T.; Cross section: Authors)

For the most part of its route the Diocletian aqueduct channel was laid on the ground, following its natural slope, with frequent horizontal and vertical deviations. The channel was built in the ditch of variable width. The walls are built roughly of crushed stone, with abundant use of lime mortar with fragments of brick. The bottom is of thick layer of red waterproof mortar. The corners of the channel are filled with same mortar thus narrowing the bottom of the channel to 30 cm (1 foot). The entire interior of the channel is plastered with three layers of mortar: red lime (waterproof) of average thickness 1.5 cm, white lime with brick fragments, of average thickness 1 cm and a final layer of red waterproof mortar of average thickness 0.5 cm. The vault is 30 cm (1 foot) high and 20-25 cm thick. The vault is built of broken laminated stone with abundant use of mortar. It is plastered with red waterproof mortar on the inside and smoothed by lime mortar on the outside, Fig 5. This construction provided good watertightness in all operating conditions. Multi-layer plastering, together with covering of the channel provided good thermal insulation of the water in the channel. Average water temperature at the spring is 15^0C with very small fluctuations, so that the temperature of the water flowing into the Palace was nearly equal to what is usually considered ideal for consumption. Multilayer plaster and construction method also prevented leakage of the channel in case of minor earthquakes or horizontal ground motion.

From the Jadro spring the channel runs along the left bank of the river. In order to cross over small valleys, four small bridges were built with a 2-4 meters span. On the second kilometre of the route the channel intersects a natural reef through a cut called "Prosik", Fig 6, and on the third kilometre it runs through a 287 m long tunnel.

The four valleys that lie between the third and fifth kilometre, are spanned by larger bridges: "Karabaš" (length 156 m, slope $2.43^0/_{00}$), "Bilice" (length 69 m, slope $2.38^0/_{00}$) "Mostine" (length 234 m , slope $2.43^0/_{00}$) and "Smokovik" (length 114.5 m, slope $2.659^0/_{00}$).

The channel runs between the last two bridges through a 120 m long tunnel, (Katanić, Gojković 1972). The construction and architecture of aqueducts Karabaš, Bilice and Smokovik, which differ from the aqueduct Mostine, is very similar. Of the four big bridges only the Mostine bridge remains largely preserved in its original form. The other three were built in the late 19th century during the restoration of the Roman aqueduct.

Figure 6. "Prosik" cut

Figure 7. "Bilice" bridge reconstructed

Archaeological excavations at Bilice under the existing bridge, built in the late 19th century, yieled remains of Roman bridge piers with beginnings of the arches were found. The piers were built of crushed stone, and the arches of the bricks 36x36x4cm, (Gudelj 1999). As one part of the bridge had to be destroyed during the construction of the road, it was reconstructed in its original Roman form, over the reinforced concrete structure above the road, Fig 7.

The bridge of the Mostine aqueduct is 234 m long, 15 m high and 2.4 m wide. It is built of large carved stone blocks interconnected with metal cramp, Fig 8. Judging by the old photos before the renovation of the bridge, only columns and arch intrados were preserved. Therefore, in medieval documents and drawings, this bridge was called "dry bridge". Everything above that was reconstructed, and the shape of the mouldings that decorate the face of the arches were taken from the northern gate of Diocletian's Palace. Today the bridge has 19 arches, of which 17 are of the same span, while the two central ones are nearly twice as big. Originally, there were more arches on the side of Split, but during the reconstruction at the end of the 19th century a solid wall was built in their place.

Figure 8. "Mostine" bridge

On the fifth kilometre of the route the channel runs through a 1268 m long tunnel, Fig 9. The tunnel was dug in marl and its profiles vary, which is related to natural marl layers that form the vault, Fig 11. An ancient masonry channel 60/120 cm in section, was laid in the tunnel and is preserved in large part with the original red mortar. The route of the tunnel does not follow a straight line, but winds, so it can be assumed that the builders followed the marl layers, avoiding those of solid limestone which are typical for the Split peninsula.

On the route of the tunnel there are 32 vertical shafts, of which 23 are blind and 9 are open, but covered with concrete slabs, Fig 12. These shafts are used for digging tunnel. They were densely placed at the beginning and end of the tunnel where the shaft height was lower, while towards the middle they were sparsely arranged. Once the vertical shaft was dug to the channel alignment, the digging of the horizontal tunnel pipe began in two directions, and the shaft served for taking out the material. In this way more working spots were opened during the digging of the tunnel, which significantly accelerated its construction.

Figure 9. "Ravne Njive" tunnel

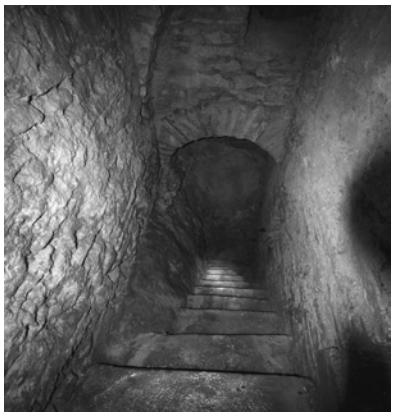

Figure 10. "Ravne Njive" tunnel staircase

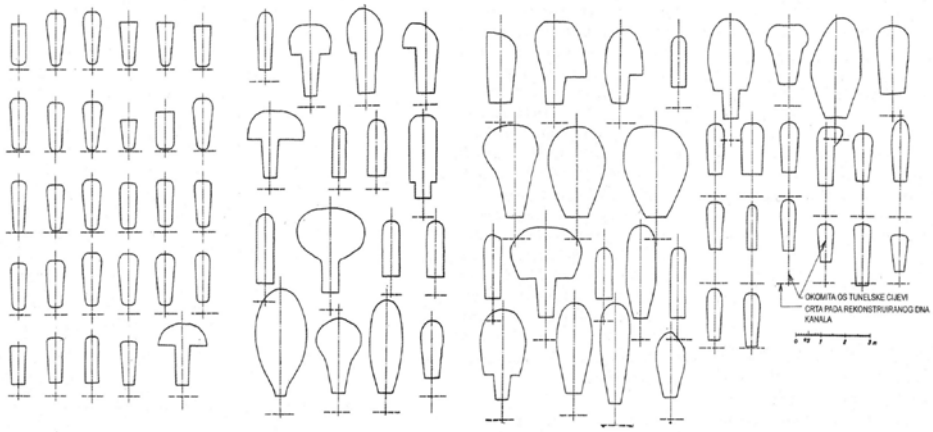

Figure 11. Cross sections of the "Ravne Njive" tunnel (Katanić, Gojković 1972)

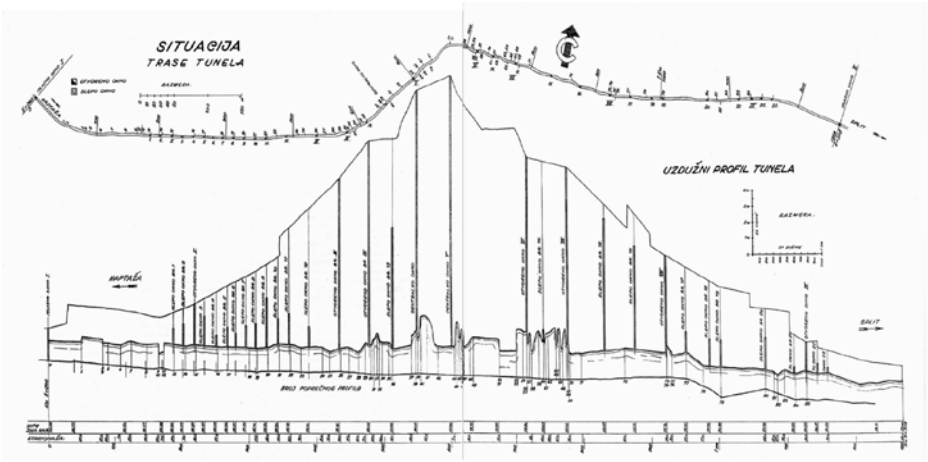

Figure 12. Longitudinal sections of the "Ravne Njive“ tunnel (Katanić, Gojković 1972)

The original Roman staircase to descend to the tunnel was preserved around the 17 m high central shaft, Figure 10. The tunnel was in function of Split water supply until 2004, when in a front of the tunnel a new water pumping station "Ravne Njive" was built. Therefore it is possible to visit the tunnel today. The authorized water company releases a small amounts of water into the channel so that its masonry channel and marl vaults don't get dry and therefore collapse. This does not create significant costs for the water company, because the water flows into the tunnel by gravity consuming no electricity. Also, no concession fee is paid for these quantities.

Behind the tunnel the aqueduct route follows the contour lines of the terrain. On the 7.420th kilometre of the aqueduct route a water supply pumping station was built in 1937 which was in function until 2004. On the 9th kilometre there is a water reservoir, built in 1879, which supplied the city by gravity pressed pipes. Although it wasn't in function for 60 years, a large part of the Roman aqueduct channel between the two structures has been preserved.

The last 500 meters of the Roman aqueduct route from the 1879 water reservoir to Diocletian's palace have not been defined yet. It can only be assumed that the channel followed the contour line of the terrain. Research is under way which seeks to reconstruct the position and appearance of the final section of the aqueduct.

Dispensıng structure and water network

Near the Palace the water supply ended in a dispensing structure (*Castellum Divisorium*) which has not yet been found, and which is assumed to be located on the slopes of the hill Gripe (Nikšić 2012) about 250 meters northeast of the Palace, at a height of about 20.00 m above sea. Water flowed by pressurized water supply from the dispensing structure to the Palace where it was distributed to various locations by lead pipeline, for easier use. Water flowed into bathrooms and public fountains from where it was taken for individual use. It can be assumed that the imperial rooms had a separate water network that served only the

emperor and his staff. Discharge points were free-flowing. Inside the Palace were two bathrooms, while Diocletian's personal bathroom is assumed to have been within the western part of his apartment. So far, only one fragment of the pipe of 6 cm in diameter has been found in the eastern bathroom (Marasović et al. 1972). Ruins of the eastern part of the imperial chambers yielded fragments of the only fountain found so far (Bužančić 2009).

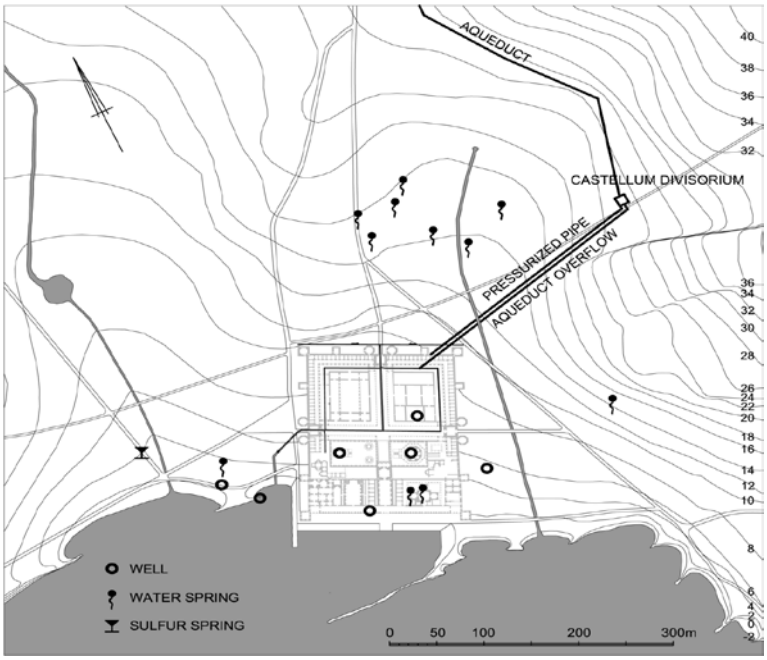

Figure 13. Assumed position of Diocletian's Palace *Castellum Divisorium* (Authors)

Discussion and conclusions

The Diocletian's Palace aqueduct is a magnificent example of Roman construction of water supply structures. Its planning and construction took into account all the factors and standards that this type of structure should have even today. The builders strived to obtain the quality and reliable construction for transport of drinking water. Dimensions and channel slope were selected so as to provide sufficient water capacity, taking into account the possible construction and construction technology in various building conditions on the ground, tunnels and bridges. Reduction of water losses, maintaining water temperature and pollution protection were also taken into account. The structure was built according to all standard principles on which the functioning of water supply systems in Roman cities was based. The uniqueness of this structure is that this system was built exclusively for the needs of the imperial Palace. It can be assumed that the construction of the aqueduct preceded that of Diocletian's Palace due to the importance of water supply for construction purposes, as well as for the organization of life of a large number of builders working on it.

The fact that large parts of the system are still used for water supply of Split testify to good planning of the Diocletian water supply system and the quality of its construction. Although the structure is 17 centuries old, it is still in operation. Unfortunately it hasn't

been sufficiently explored yet, so it cannot be fully and reliably reconstructed. This particularly relates to the beginning, water intake and the last section of the aqueduct as well as the dispensing structure. This is one of the tasks whose realization will be important in the future period. The purpose of this study is to emphasize the importance of this structure for historical understanding of the development of water supply systems, and the need for further research and analysis of this and similar historical water supply systems. We hope that historians, scientists and engineers will benefit from information presented in this paper.

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