MN-60

Water Flow to the Ancient Industrial Mill of Barbegal – La Burlande Basin

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Abstract The Roman water supply development in southern France near the present day city of Arles has long fascinated archaeologists and historians alike because of its scope and complexity. A key feature of the water system, the Barbegal Mill is the site of the largest known industrial use of water power by the Ancient Romans. This First Century project captured flow from spring water sources in the Alpilles Mountains serving the North and South Aqueducts totaling about 50 kilometers in length that converged some seven kilometers north of the Roman City of Arleate (now Arles).
The Barbegal Mill utilized 16 waterwheels to power 16 millstones. The operating capacity of the main mill site aqueduct has been estimated at between 240 and 250 liters per second (L/s). In this study, the flow capacity of the South Aqueduct was confirmed to be 250 L/s at a location known as the La Burlande Basin. The engineering field research performed at the La Burlande Basin, with a reasonable degree of certainty, supports the hypothesis that the Barbegal Mill was designed and sized to match the hydraulic capacity of the South Aqueduct.

Keywords Barbegal; Industrial Mill; Roman Aqueduct

INTRODUCTION

Roman civil engineers were masters at water resource development. They built elaborate structures and constructed aqueducts over long distances to transport water to provide their citizens with the necessities of a great empire. The important ancient water powered mill near present day Arles, France is a fine example of Roman ingenuity. The mill supplied flour to the Roman city of Arleate (now known as Arles). Agricultural lands around the growing City of Arleate provided grains, but a mill was required to turn them into flour.

The mill was designed with sixteen water wheels that each powered a millstone measuring 2.1 meters (m) in diameter. A water supply of up to 250 L/s was split into two equal channels with a total fall of about 18 m to power two rows of waterwheels of eight each in series. Thus, each waterwheel received about 125 L/s.

Two long aqueducts brought water from spring supplies in the Alpilles Mountains. These aqueducts are known as the North and South Aqueducts, see Figure 1. The water flow from each of these aqueducts jointed in a convergence box located approximately 340 m north of the mill site. From the convergence box, parallel aqueducts were carried to the south on top of arcade bridges. The convergence box provided a control point so that the total supply from the two aqueducts could be sent to Arleate or a portion could flow to the mill.

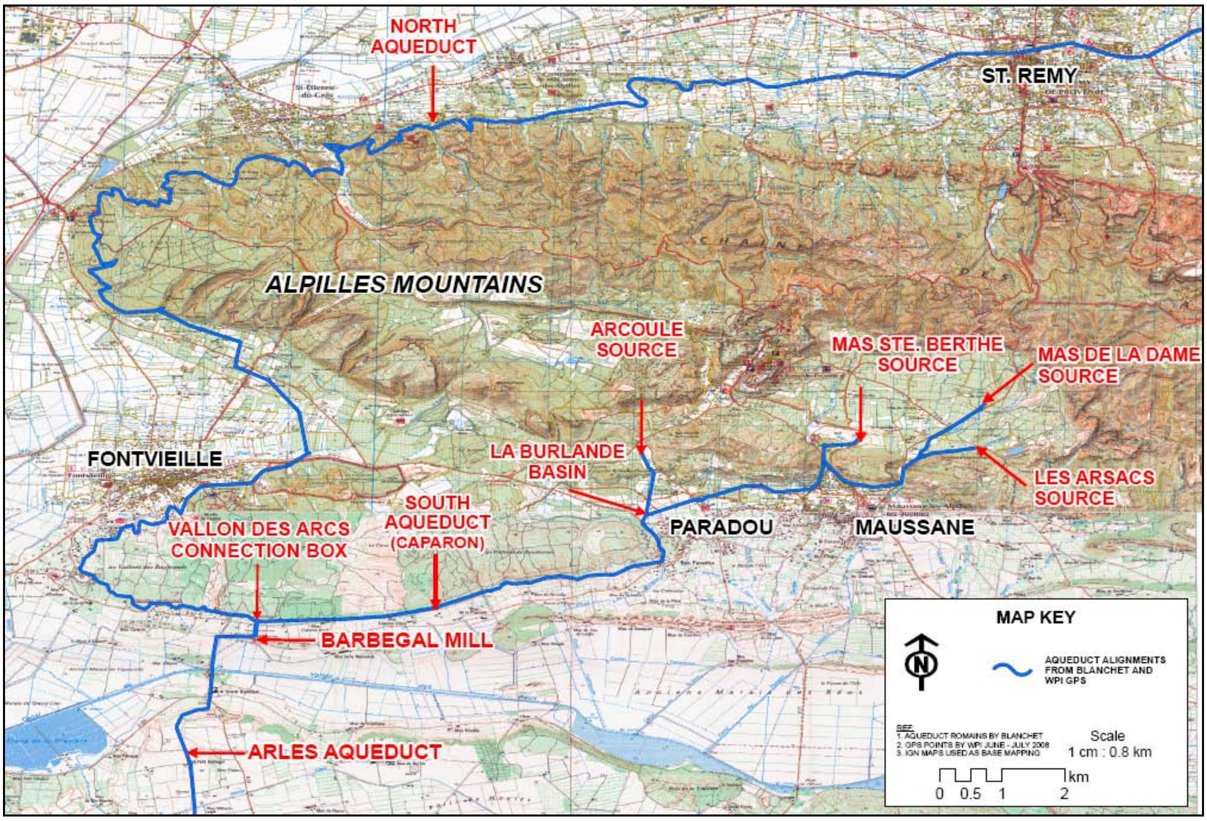

Figure 1. Barbegal mill and aqueduct system.

The Roman engineers built two long aqueducts; modern archaeologists have surmised the South Aqueduct was built first, but the evidence for proving this hypothesis was slim.

Our calculations of flow at the mill site, and previous studies by Heimann et.al. (1993), Schnitter (1972) and Sellin (1981), suggest that the total flow directed to the mill was 240 to 300 L/s. The mill operation was intermittent and controlled by harvesting periods and demand for flour.

Our studies in 2008 of a recently discovered water collection box, known as the La Burlande Box near the village of Paradou, France showed that this box was on the South Aqueduct and helped to support the hypothesis that the South Aqueduct was built first and the mill was built to use the flow of the South Aqueduct.

The 2008 field surveys and analyses concluded that the La Burlande Box was designed to deliver 250 L/s to the South Aqueduct at a point approximately 6 kilometers upstream of the convergence box, the exact flow that was released from the convergence box to the mill.

LA BURLANDE BASİN – 1988 PARADOU DİSCOVERY

In June 2008, we were fortunate to have some time to meet with our esteemed colleague, Dr. Philippe Leveau, Professor of History and Archaeology of Ancient Civilizations at Aix-in-Provence University. Dr. Leveau is the leading researcher on the Barbegal ruins and is familiar with many of the hydraulic features of the system. At our meeting, knowing our special interest in hydraulics, he suggested that we have a look at the La Burlande collection box on the South Aqueduct. He pointed out that the La Burlande box and the nearby remaining aqueduct sites had not yet been field surveyed to investigate if the channel elevations were consistent for the South Aqueduct connection to Barbegal. We decided to put our surveying instruments to work and then look at the details of the hydraulic functions of this site.

The La Burlande Basin is located in the present day town of Paradou, approximately 6 kilometers upstream from the Barbegal Mill, see Figure 1. The site is near intersection of highway D17 (Route d'Arles) and the Chemin de Saint-Eloi as shown on Figure 2.

Figure 2. La burlande basin and south aqueduct.

The basin and downstream aqueduct section were discovered relatively recently, in 1988 during the construction of a campground. Along with the basin, on this site was discovered the fascinating cut stone abutments of an ancient road bridge crossing of the aqueduct. Located only 44 meters from the La Burlande Basin, the bridge carried the famous Via Auerilia that was a major highway between Aquae Sextiae (now Aix-en-Provence) and Arelate (now Arles) for Roman trade and transport. The bridge abutment stones are 7.8 meters long, which is consistent with the dimensions used by Roman engineers for major highways in the empire.

SOUTH AQUEDUCT AND SLOPE

The ancient alignment of the channel downstream from the basin is across highway D17 and along the edge of a neighborhood (Domaine des Alpilles de Paradou) as shown in Figure 2. During the construction of this residential area in 1988, several remains of the aqueduct were uncovered. Built on the side of a hill, these were tunneled channel sections. One of these sections was located at the Regard Coin Rues, in a residential yard on a street corner. This is an important site to our investigation since this is the first existing channel with an accessible invert downstream of the La Burlande site.

The Regard Coin Rues is an open shaft that has a modern railing around it to protect people from falling into the opening. The tunneled channel has an accessible invert at about 2 m below grade. This is one of the sections where we obtained an invert elevation through field survey, see Figure 3. This location is approximately 392 meters from the La Burlande Basin. Field surveying was performed using a surveyor's level for this investigation. The length of the aqueduct channel was measured by surveyors tape on the La Burlande site (up to the end of the existing channel). Since there are only a few archeological sites where the aqueduct still exists, the distances between the Burlande site and the Barbegal Mill were estimated from scaling maps and aerial photographs.

Table 1. Field survey data – slope of aqueduct segments

Location	Distance from La Burlande Basin (meters)	Length of Segment (meters)	Elevation (meters)	Elevation Difference from Last Location (meters)	Slope of Segment
Basin Outlet	-	-	29.38	-	-
Chute End	1.8	1.8	29.11	0.27	0.15
Section 1	34	32	28.53	0.58	0.018
End of Existing Channel at Burlande Site	64	30	28.22	0.31	0.010
Regard Coin Rues	392	328	27.58	0.64	0.002
Tunnel Section East of Convergence Box	5328	4936	24.61	2.97	0.0006
Vallon de Arcs Convergence Box	5620	292	24.55	0.06	0.0002
Barbegal Mill	5960	340	24.01	0.54	0.0016

Figure 3. Regard coin rues shaft and top of tunneled section.

These results show that the La Burlande Basin is at a consistent elevation with respect to downstream elevations of the South Aqueduct that connects to Barbegal. The slope of the channel is steeper in the area of La Burlande and begins to flatten out as the aqueduct nears Barbegal. The La Burlande Basin was indeed a structure on the South Aqueduct on this upper location to capture the water sources from L'Arcoule (located in Les Baux de Provence) and Maussane area springs for transport to the Barbegal Mill.

Also, of importance to our work is that there has been no other spring sources discovered that fed into the South Aqueduct between the La Burlande Basin and the Barbegal Mill.

LA BURLANDE BASİN – DESCRİPTİON

The La Burlande box was designed to be the convergence of two inlets with an outlet to the downstream South Aqueduct channel. A photograph of the basin is presented in Figure 4.

Figure 4. La burlande basin.

The remains of the channel extend downstream for a total of 64 meters, where the existing channel ends, see Figure 5. This section of the South Aqueduct channel was hewn out of limestone blocks that are joined together, rather than the brick and mortar techniques used in other sections of the aqueduct.

Figure 5. South aqueduct la burlande channel – downstream of basin.

The La Burlande Basin, as shown in Figure 6, was constructed with large limestone blocks and has the interior dimensions of 2.5 meters by 3.0 meters. The blocks have been fitted together without the use of mortar.

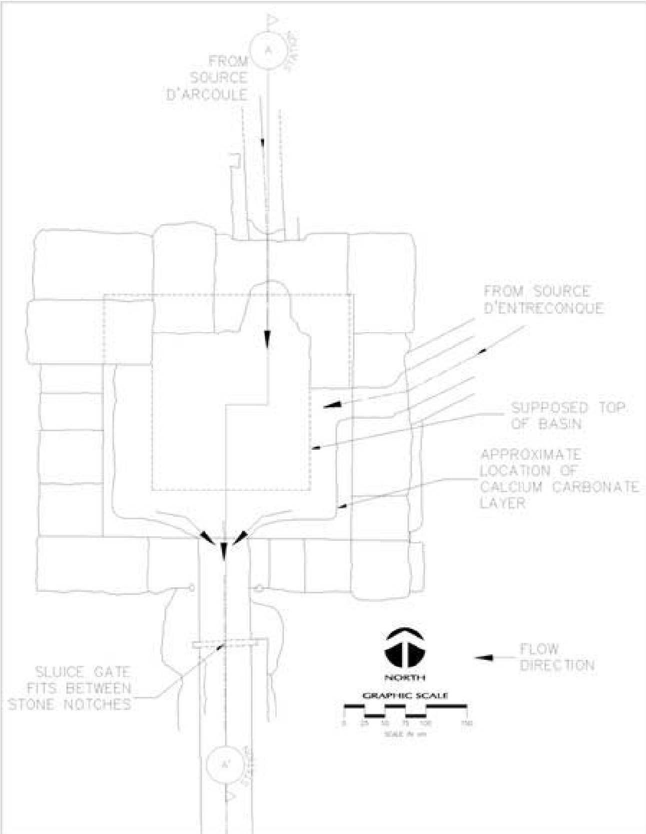

Figure 6: La burlande basin – plan (after Jean Louis Paillet IRAA CNRS, 1988).

The basin is a major hydraulic structure that had to have hydraulic significance to the Roman engineers. The depth of the basin has not been fully established. In 1988, partial excavation on the outside of the box was to 2.18 meters and showed a total of four stacked stone rows. The excavation apparently did not extend to the bottom of the structure.

The box is constructed over a spring, with fresh groundwater entering the bottom of the box. During the days of inspection (in June 2008) the groundwater level was below the box outlet elevation.

There are two small channel inlets to the box located on the north and east sides. The north inlet is from several spring sources in the area of present day Town of Maussane; therefore, this inlet is called the Maussane inlet. This inlet has the dimensions of 43 cm wide by 45 cm deep. The east inlet brought spring water from the L'Arcoule spring.

The outlet of the box was of particular hydraulic importance to the South Aqueduct. It is located on the south side of the box with the dimensions of 62 cm wide and 20 cm deep as it exits the box. There are notches that are evident in the limestone blocks that are approximately 125 cm downstream of the box, see Figure 7. These notches are the guides for a slide gate that provided flow control from the box.

Figure 7. Notches for slide gate.

LA BURLANDE BASİN – HYDRAULİCS

Roman engineers used many types of collection and junction boxes for various uses in aqueduct systems. Collection boxes were used for infiltration galleries and springs as a beginning of water journey along the aqueduct channel to the point of use. Distribution boxes were used to provide hydraulic control, by the use of gates, for distribution.

The study of the details of the La Burlande Basin shows that it was designed with hydraulic flow control. This control may have been used to deliver the desired flow for industrial use at the Barbegal Mill, some 6 kilometers downstream.

The notches in the limestone blocks just downstream of the outlet from the basin are shown in Figure 7. The configuration of channel bottom just downstream of the basin indicates that the type of slide gate used in these notches was of a sluice type, rather than a weir overflow type. A sluice gate requires a short downstream section that has a steeper slope so that supercritical flow conditions occur which would prevent a hydraulic jump and promote linear, uniform flow on the downstream side of the gate. This is the condition just downstream of the basin. The slope (creating a kind of chute) downstream of the sluice gate helped the sluice gate operator obtain more predicable flow from the sluice gate.

Using the equation for a sluice gate, the range of flow rates from the La Burlande Basin can be approximated by a linear function for various head water depths, H, as shown on Figure 8.

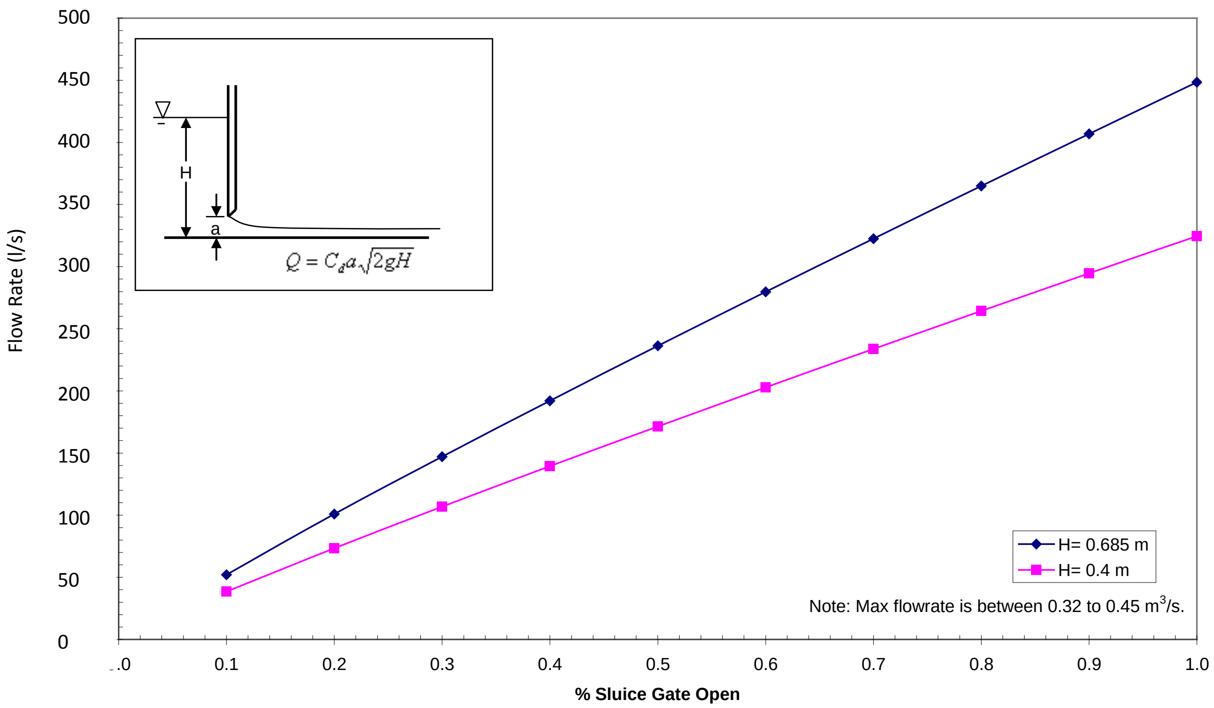

Figure 8. Sluice gate range of flow.

The transition of channel bottom slopes as measured downstream of the sluice gate location may impose a hydraulic jump, depending on the flows in the channel. In hydraulic design, downstream slope conditions can impose non-linear, turbulent flow conditions that would limit the channel flow. The channel slope conditions at La Burlande indicated to us that there would be a transition from supercritical flow to subcritical flow, which could limit the range of flows that could be obtained by the sluice gate operations. This transition was investigated by using hydraulic engineering methods: calculating velocity of flow (using Manning's equation), calculating the Froude number, and locating/determining the depth of flow at the hydraulic jump.

The results of this approach showed that the flow transitioned from supercritical to subcritical flow at a flow of greater than 150 L/s. This would have resulted in a hydraulic jump near the transition from steep to mild slope.

The most interesting result of the evaluation was that the height of the hydraulic jump was at the top of the existing aqueduct channel sidewall at flows of about 250 L/s, as shown in Figure 9. The jump occurred at a distance of between 30 and 40 meters. Flows that were greater than 250 L/s were calculated to overtop the sides of the channel.

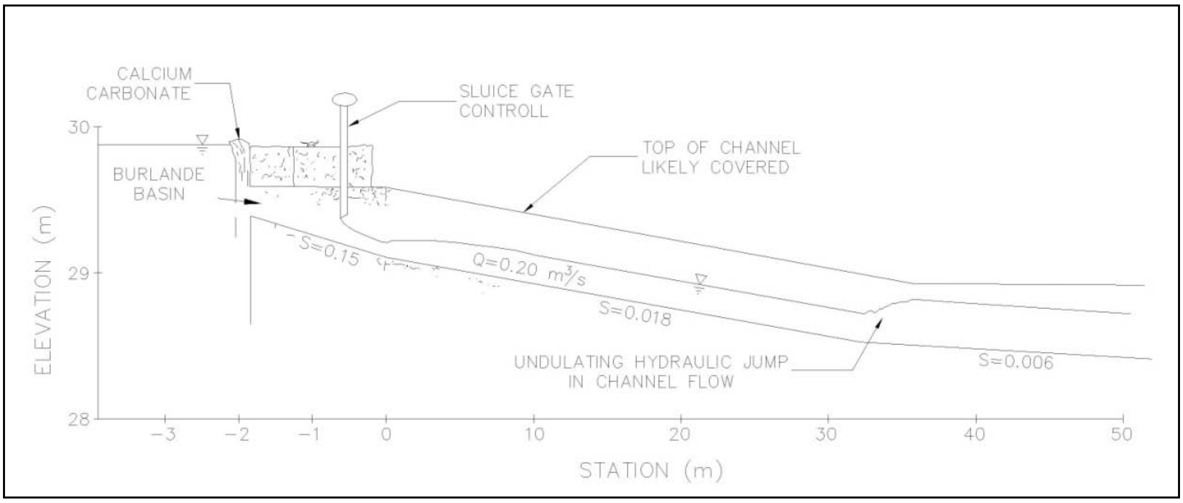

Figure 9. Flow conditions downstream of la burlande basin at Q = 250 liters per second.

Therefore, the control of the sluice gate at the La Burlande Basin was to control the maximum flow that could be carried in the near downstream section from the La Burlande Basin. The limiting flow at the La Burlande Basin that was calculated by modern hydraulic methods verifies the flow that was calculated within the channel just upstream of the Barbegal Mill at 230 to 250 L/s.

CONCLUSİONS

The La Burlande Basin was verified by field surveying as a feature on the South Aqueduct serving the Barbegal Mill. The slope of the South Aqueduct decreased from the La Burlande Basin to the Barbegal Mill to a mild 0.0002 just before the Mill.

Hydraulic assessment of the La Burlande Basin on the South Aqueduct feeding the Barbegal Mill shows that flows were controlled at this basin to deliver from 250 L/s. Higher, and uncontrolled, flows would have resulted in hydraulic jump conditions just downstream of the basin that would have overtopped the channel walls.

This work verifies previous independent studies of the channel flows some 6 kilometers downstream of the basin location: that the La Burlande Box was designed to deliver 250 L/s to the South Aqueduct at a point approximately 6 kilometers upstream of the convergence box, the exact flow that was released from the convergence box to the mill.

As a result it can be concluded with a reasonable degree of engineering certainty that the South Aqueduct was built first and the mill was built to use the flow of the South Aqueduct. When the mill was not in operations, the south aqueduct water would be routed to Arleate.

ACKNOWLEDGMENTS

The authors would like to thank Wright Paleohydrological Institute and Wright Water Engineers, Inc. for support.

REFERENCES

Heimann, S; Drewes, U; Leveau, P., “Discharge Calculations for the Roman Aqueducts at Arles and the Mills of Barbegal”, Wasserwirtschaft Vol. 83, 1993.

Sellin, R.H.J., The Large Roman Water Mill at Barbegal (France)

Schnitter, N. Wasserbaugeschichtliche Exkursion in die Provence, Wasser and Energiewirtschaft, 3/1972