

Following Roman Waterways from a Computer Screen. GIS-based Approaches to the Analysis of Barcino's Aqueducts

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Abstract

From the 1950's until today the Roman colony of Barcino (modern Barcelona) has been believed to possess two aqueducts. One was transporting water from the Montcada mountains and the other one from the Collserola range. In this article, GIS-based least-cost route analysis (LCR) in combination with more traditional archaeological techniques is applied to analyse these aqueduct's routes. The results obtained suggest Barcino had only one aqueduct: the one carrying water from Montcada. The aqueduct was divided in two channels before entering the city, thus giving origin to the theories suggesting the existence of two aqueducts. LCR analysis has also been useful in determining the medieval transformation of this aqueduct into the Rec Comtal water channel.

Introduction

Water supply was a key function of Roman public services, it covered numerous public and private needs in Roman cities. Roman engineers were particularly efficient at designing and constructing water collecting, transport, storage and distribution systems which supplied public and private baths, fountains, gardens and pools, dwellings and industries. Roman cities consumed significantly more water per person than modern ones, at least judging by the example of Imperial Rome (FORBES 1955, HODGE 2000, 47–49). It is not clichéd to state that Roman culture was intimately related to water use (ORENCO ET AL. IN PRESS). Not in vain, PLINY THE ELDER (Nat. XXXI 2.4) evokes the power of water to create cities. Therefore, the choice of an adequate source of water was an important one. Different types of water were selected according to their intended use, that being medicinal, potable, sanitary, industrial or recreational. Some of the most noteworthy examples in this sense are the construction of the Aqua Alsietina, an aqueduct directed at supplying the Naumachia of Augustus, an artificial lake in the Trastevere in which recreational naval battles would be performed or the Aqua Virgo, constructed to supply the *thermae* of Agrippa in Campo Marzio (STACCIOLI 2002, 56–65). Transporting water from far away sources could easily pay off the large effort required to achieve this, when a constant and adequate supply was guaranteed and the water was pure enough. Roman authors, in fact, attached much importance to water qualities (VITRUVIUS 8, 4, 1–2; FRONTINUS 11, 1–2). Water quality could save maintenance costs preventing the settling of sinter on the channel walls or silt at the bottom. In this sense, Roman engineers were, to a certain degree, more concerned about the quality and quantity of water supplied



Figure 1. Aqueduct entrances into the city.

by a certain source than the distance the water had to be transported (HODGE 2000, 49; MALISSARD 2001, 151–153). Numerous examples can be provided which show the enormous distances covered by aqueducts to obtain good quality water in exchange (HODGE 2000, 65).

Barcino's aqueducts

This work intends to present the first results of a project dedicated to the study of water sources, management, distribution, use and disposal in the Roman colony of Barcino (modern Barcelona). The project was started in 2009 by the Catalan Institute of Classical Archaeology (ICAC) and the Museum of the History of Barcelona (MUHBA) (MIRÓ – ORENCO 2010). The first stage of the project consisted in the analysis of Barcino's Roman aqueducts. Since the 1960's it is considered that this city was supplied with water from different springs by means of two aqueducts. This belief came from the discovery of two aqueduct channels in the tower of one of Barcino's Roman gates (*figure 1*). This tower was the entrance for the water channels to the city for its urban distribution. Later, excavations carried

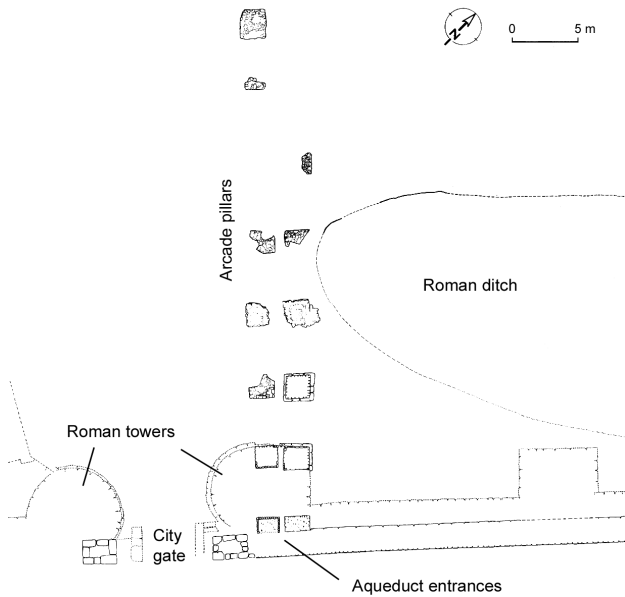


Figure 2. Arcade pillar bases archaeologically documented.

out next to this tower, unearthed a series of pillars corresponding to the two arcades bearing the channels found inside the tower (figure 2). These findings were interpreted as being part of two aqueducts carrying water to the city from different sources which joined at this point to enter the city through the same entrance.

A short history of the research carried out about them, referred as the Montcada and the Collserola aqueducts from this point onwards, is presented here.

The Montcada aqueduct

Evidence of this aqueduct can be found in written documents dating back to the Xth century. The discovery in 1987 of a preserved arcade of five contiguous arches with the aqueduct channel still intact on top of them, some 160 m away from the Roman city gate contributes to the written evidence concerning the form and route of this aqueduct inside Barcelona's medieval quarter. The recent discovery of a 90 m subterranean stretch of aqueduct at 6.7 km north of the city (GINER 2006) corroborates the idea, already suggested by the medieval documents, that this aqueduct supplied water from the springs located in the Montcada mountains, some 9 km north from the city. Most of the aqueduct was a subterranean conduit which, as it approached the city was elevated by means of arcades. This conduit route has been generally acknowledged to coincide with that of Rec Comtal, a Xth century channel used to supply hydraulic energy for numerous mills and water to irrigate several areas of Barcelona's plain. Early medieval documents and archaeological evidence seem to support this theory. The route of Rec Comtal, unlike that of Montcada aqueduct's, deviated before reaching the Roman city cen-

tre in order to provide water to the industrial areas of the medieval city.

The Collserola aqueduct

The analysis of XVIIth and XVIIIth century documents and toponymic evidence lead MAYER AND RODÀ (1977) to propose that the Collserola Range springs were the origin of this second aqueduct. They also proposed a route for this aqueduct which traversed Barcelona's plain in a straight line from Collserola to the entrance of the aqueducts in Barcino equivalent to that of the XIVth century pressurized piped conduit which supplied the fountains of medieval and modern Barcelona (XIVth–XVIIIth centuries).

Sources and Methods

The cartographic database

In order to study the characteristic features of Barcino's aqueducts, a specific GIS-based cartographic dataset had to be constructed. This posed a number of problems that are not usually acknowledged in GIS-based landscape studies. Firstly, and most importantly, Barcelona's territory has undergone dramatic change since the Roman period (PALET 1997; PALET ET AL. 2009). Such landscape changes, which have mostly occurred during the second half of the XIXth and the XXth century, have had irreversible effects on the territory's topography, rendering modern digital terrain models (DTMs) useless. In order to somewhat reduce the effects of modern construction work in the area, a series of XIXth century and early XXth century topographic maps were selected and georeferenced using a regressive cartographic database. That is, modern maps were employed to obtain Ground Control Points (GCPs) which in turn could be used to georeference older ones from which new GCPs could be obtained. This process permitted the creation of a database with more than 300 of no longer available GCPs which in turn allowed georeferencing the oldest cartographic elements. The combination of the different georeferenced old topographic maps permitted a reading of the area without the most evident modern landscape modifications and thus facilitated the development of a hypothetical topographic map of the area in pre-industrial times.

The geographic database also included a series of 1:2.000 aerial photographs made in 1947. These were georeferenced and orthorectified using GCPs obtained from the georeferenced cartographic database.

Reconstruction of the Rec Comtal route

The analysis of old cartography and old aerial photographs was employed to locate ancient traces of the Rec Comtal route. By combining the morphological information present in georeferenced ancient maps and orthophotographs, the Rec Comtal route was reconstructed (figure 3) to a high degree of precision (a maximum ground error of 1.5 m).

Written and archaeological evidence

The first step in the study of Barcino's Roman aqueducts

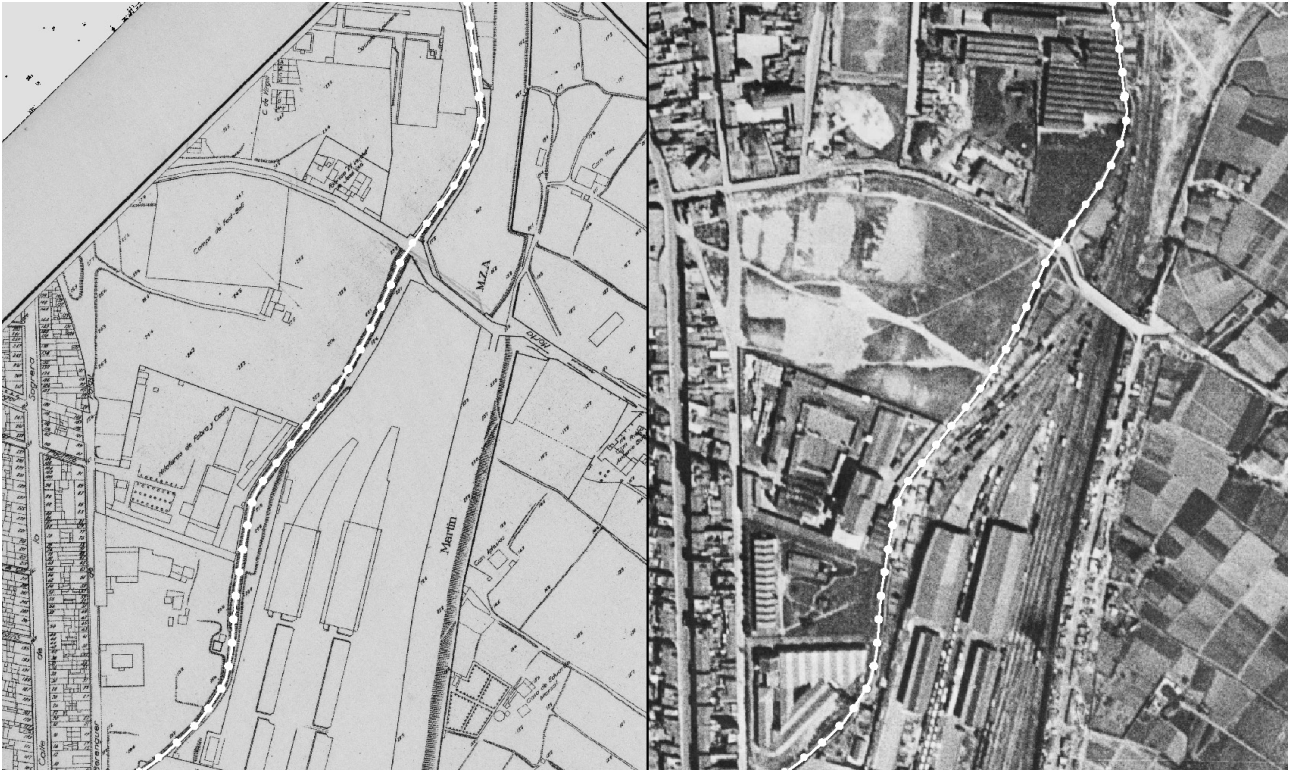


Figure 3. Cartographic and photographic reconstruction of the Rec Comtal route.

was the positioning of the different types of evidence which can offer any geographically located information on the ancient trace of the aqueducts. Medieval written evidence which related to the location of the aqueducts was also introduced in the GIS. A total number of 25 documents corresponding to dates between the Xth and the XIXth century were introduced into a database which contained their geographical location, their documentary reference and the quoted text. An epigraphic document in Latin found in Camí de Jesús which related to the city's water management was also introduced. Another layer was constituted by the archaeologically documented remains of the aqueducts. Their plans were digitised, georeferenced and vectorised.

Least Cost Route Analysis

LCR has been employed in the analysis of Roman aqueduct routes before (BAENA ET AL. 1998; ROLDÁN ET AL. 1999, LAGÓSTENA – ZULETA 2009, 165-166). Unfortunately, there is little explanation in these works about the methodology followed or the algorithm employed. This might be caused by the fact that Least-Cost Route (LCR) analysis alone cannot be employed to model the trace of a water channel. Due to the specific characteristics of aqueducts which combine a constructed trace and a water flow, they do not obey cultural, topographic or hydrologic conditionings alone but a combination of them all. None the less, aqueducts are landscape structures, they adapt to the territory's topography to a certain extent (HODGE 2000, 54–55) and this essential topographic adaptation makes LCR analysis an especially adequate tool to analyse them.

Having said that, several characteristics of aqueducts have to be taken into account when modelling their route:

- They only flow in one direction so anisotropic models are to be preferred.
- They follow a downhill route.
- Their gradient is constant.
- Excessive downward slope is not supported by unpressurized conduits.
- They can also incorporate engineering works such as cascades, tunnels, siphons or arcades which allow them, to a certain degree, to overcome topographic restraints.
- They also show an interest in monumentality which can motivate the use of arcades when not topographically necessary.

The development of LCRs based on cost surfaces has been acknowledged as a useful methodological approach in the archaeological analysis of movement. However, as has already been pointed out, the use of LCR alone cannot produce valid results but it should be directed towards an exploratory analysis (Fiz and Orenge 2008). In this sense, the results of the cartographic and photographic analyses of the Rec Comtal and the locations suggested by the different documents referring to the aqueduct's traces will be essential in modelling the most appropriate route. The model will be tried and refined using the archaeological evidence known for the Montcada aqueduct. This model will then be applied to the reconstruction of the second aqueduct, the one bringing waters from the Collserola Range.

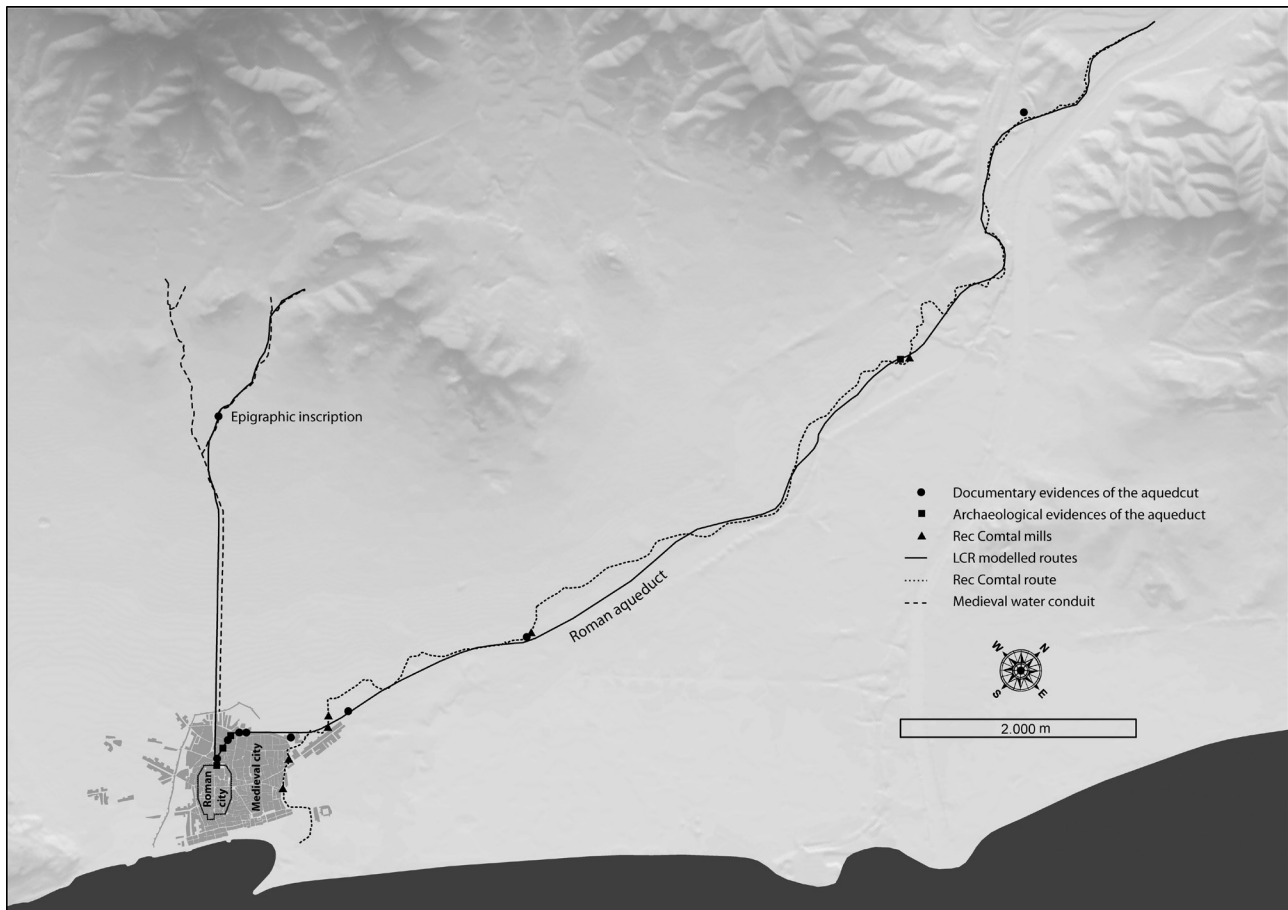


Figure 4. Reconstruction of the Roman aqueduct, the Rec Comtal and Medieval conduit routes.

To develop a cost surface which could effectively reflect the friction parameters affecting the route of the aqueduct, the GRASS GIS module *r.walk* was chosen (FONTANARI 2002). This anisotropic function incorporates the formula published by AITKEN (1977) and LANGMUIR (1984) based on Naismith's rule for walking times:

$$T = [(a) * (\Delta S)] + [(b) * (\Delta H \text{ uphill})] + [(c) * (\Delta H \text{ moderate downhill})] + [(d) * (\Delta H \text{ steep downhill})]$$

Where:

T is time of movement in seconds, ΔS is the distance covered in meters and ΔH is the altitude difference in meters. The default parameters, developed originally to calculate walking times, were adapted to define the factors involved in the setting of a Roman aqueduct thus favouring moderate downhill and strongly discouraging both uphill and steep downhill movements:

a (cost of movement): 0.5

b (cost of movement uphill): 200

c (cost of movement moderate downhill): 0.1

d (cost of movement steep downhill): -200

The slope value threshold is -0.017 (corresponding to $\tan(-0.974^\circ)$). Values exceeding this threshold will be regarded as steep downhill and they will therefore incur in increased cost values. As HERZOG has pointed out (2010), the *r.walk* function can be inadequate when calculating

walking costs due to the harsh cost increase marked by the slope threshold. In this case study, the threshold is equal to the maximum evidenced slope of an unpressurised Roman aqueduct, corresponding to a slope of 17 m/km or 0.974° . Beyond this value Roman engineers would employ techniques such as cascades of arcades which will enormously increase the aqueduct's cost. In this sense, the *r.walk* function inadequacies for calculating walking times can be overcome when applied to the analysis of water channels. The *r.walk* module also permits to employ the knight's move in the cost surface generation which results in a more accurate analysis.

Once generated the least cost surface, the aqueduct route was determined by the module *r.drain* which would trace a water flow from the origin point through the *r.walk* generated cost surface until the aqueduct entrances into Barcino. The results of this analysis will be useful in gaining a better knowledge of the conditions affecting the design and construction of Barcino's Roman aqueducts as well as to analyse their routes.

Results

The Montcada aqueduct

The proposed LCR for the Roman aqueduct of Montcada coincides with the path followed by Rec Comtal as evidenced by cartographic and photographic interpretation. It is also coincident with the archaeological and documentary evidence of the Roman aqueduct. Two main differences have been encountered between the routes followed by the Rec Comtal and the Roman aqueduct (figure 4). Firstly, Rec Comtal diverts before entering the Roman city. Secondly, the trace of Rec Comtal is clearly more sinuous than that of the LCR modelled Roman aqueduct. It shows various diversions which at first follow the contours and later break them to get the maximum slope until it reunites with the ancient aqueduct trace. Ancient map analysis and documentary evidence show that these deviations coincided with the location of medieval and modern mills. After detailed microtopographical analysis it becomes obvious that these deviations' purpose was to keep the water flow level only to later make it descend abruptly and thus take advantage of the increase in water speed. Mills were constructed at the points of highest water speed (figure 5).

The Roman aqueduct was employed in the Middle Ages as a topographical guide in the construction of the Rec Comtal open channel. This use has also been documented in the construction of Mina de l'Arquebisbe, a water conduction which also followed the traces of one of Tarraco's Roman aqueducts (LÓPEZ 2008, 368).

The total length of the aqueduct would be 11.3 km covering a total height difference of only 18.12 m. The water flow inclination would be 1.6 m/km, a rather conservative proportion for a Roman aqueduct according to the standards recorded in the archaeological bibliography (HODGE 2000, 50–51). There was indeed some divergence amongst Roman authors: VITRUVIUS (VII 6.1) specified a 5 m/km slope, whereas PLINY (Nat. XXXI 57), closer to the actual archaeological evidence, stated that the ideal slope had to be 0.2 m/km.

The Collserola aqueduct

Concerning the Collserola aqueduct, the proposed LCR shows a remarkable similarity with the traces of the medieval conduit bringing water from the Collserola springs. However, no archaeological trace of its existence in Roman times has been found. XVIIth and XVIIIth century documentary evidence relates to the medieval water conduits only. The inscription found at Camí de Jesús can also be linked to this medieval conduit. Epigraphic analysis conducted by D. Gorostidi indicates a XVIth-XVIIth century origin for this document. It may be related to a modern monumentalisation of the medieval conduit.

The LCR proposed route for this conduit was 6.4 km long with an average slope of 38.45 m/km. This slope (figure 6) is significantly higher than any other known Roman aqueduct or inverted siphon system. This is so, even if only

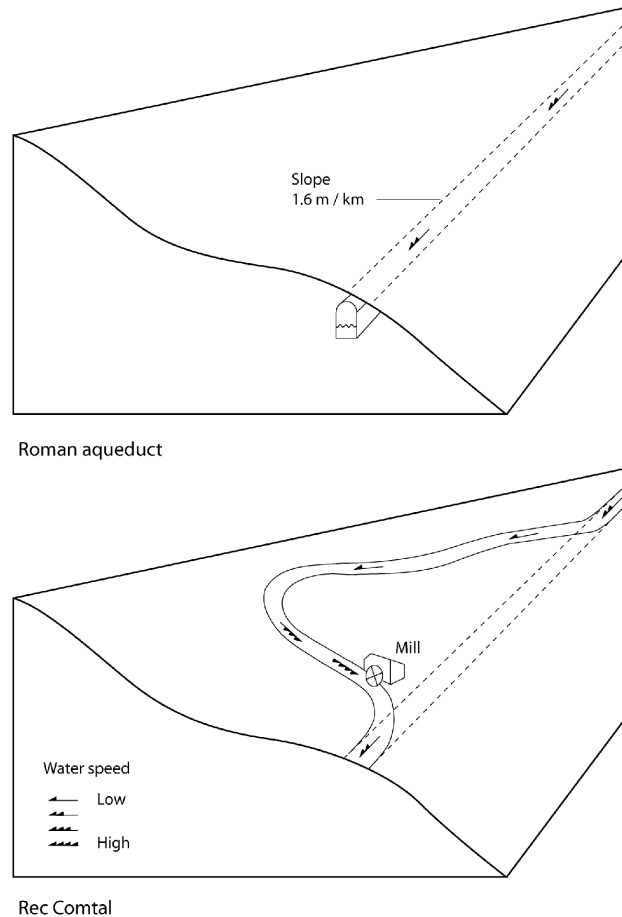


Figure 5. Comparison between the Roman Montcada aqueduct and Rec Comtal.

the last part of its route, outside Collserola range, is considered. In this case the distance would be of 2.98 km with a gradient of 17.87 m/km.

Conclusions

Historical conclusions

Considering all the data provided by the different sources, the Roman origin of the Montcada aqueduct becomes evident, whereas the Collserola aqueduct does not meet Roman engineering standards and does not show any evidence of a pre-medieval origin. It is also interesting to compare the varying water discharge levels of the different water sources. The Montcada water mine had, according to a technical enquiry conducted in 1895, a minimum discharge of 38804 m³ per day (MARTÍN 2007, 313) while the Collserola water mines discharged around 300 m³ per day (CALL 1878, 124). This is clearly an insufficient amount to justify the construction of a water conduit, particularly if the amount of water supplied by the Montcada sources is taken into account.

Furthermore, the quality of water that these channels transport should also be taken into account. The preserved stretches of channel from the Montcada aqueduct do not show any evidence of sinter deposits within them. On the

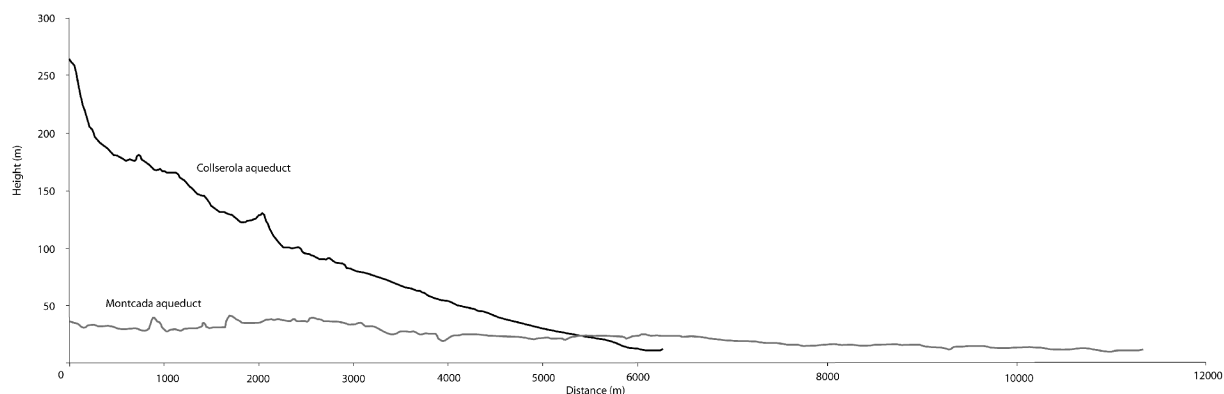


Figure 6. Comparison between the Collseorla and Montcada aqueduct profiles.

contrary, medieval documents recording water transport from the Collserola range springs made evident the need for continuous cleansing of sinter deposits in the water conduit (SCHWARTZ – CARRERAS CANDI 1892, 385; VOLTES 1967, 28, 38). In this respect, it is worth mentioning that the two channels entering Barcino presented no traces of sinter.

All this evidence leads us to assume Barcino had only one aqueduct, corresponding to the Montcada aqueduct, which considering the colony size was more than enough to cover its needs. The existence of two aqueduct entrances to the city must be related to a split of the Montcada aqueduct before entering the city. The water transported by these two channels was probably destined to cover unrelated functions within the city.

The Collserola conduit needs to be considered as medieval in origin. At the Xth century the Roman aqueduct has fallen into disuse and the Rec Comtal water was destined to agricultural and industrial functions and therefore many wells had to be excavated throughout the city to replace the water brought in by the Roman aqueduct. Some factors such as population growth or processes of desiccation and salinization of the wells probably forced medieval authorities to construct this new conduit in order to supply the medieval city towards the second half of the XIVth century.

Technical conclusions

The use of GIS and related topographic analysis has been essential in order to analyse the route of the aqueducts and its relationship to the landscape topographic settings. In the case of the Montcada aqueduct these analyses allowed the comparison between the Roman aqueduct and Rec Comtal evidencing the relationship between the Rec Comtal deviations and the new function of the medieval channel. They also provided information which allowed discarding the Collserola range as the origin of a second Roman aqueduct, as it has been believed up until now.

It is also evidenced that LCR analysis should be employed as an exploratory rather than an explanatory tool. Only by combining LCR with archaeological and historical data LCR can provide useful hints about the route of

topographically related structures in the landscape such as roads or aqueducts and the way they were conceived and constructed.

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