A GIS-based assessment of the Byzantine water supply system of Constantinople

F. Ruggeri, M. Crapper, J. R. Snyder and J. Crow

ABSTRACT

Despite the extensive archaeological surveys carried out in the last decades, little attention has been paid to one of the longest water supply systems of ancient times – the Byzantine water infrastructure which fed Constantinople from the mid-late fourth century AD. This work uses modern satellite terrain data and Global Positioning System (GPS) data to assess this system and provide an improved description of its route, total length and gradient profile. Forty-four validated GPS Control Points were correlated with ASTER GDEM V2 digital satellite data and archaeological information in a Geographic Information System (GIS) environment. We concluded that the total length of the water supply system was 426 km, and possibly even 565 km if the fifth-century aqueduct continued in parallel all the way to Constantinople rather than merging with the fourth-century aqueduct. The gradient of the channels varied across their length, being steepest near the spring sources, with a gradient mostly in the region of 5 m/km, and flattest at around 0.4 m/km in the most downstream section nearest the City. This reconstruction of the gradient profile provides valuable insight into the physical characteristics of the system, allowing future study of its hydraulic function.

Key words | Constantinople, GIS, gradient, length, Roman aqueduct, water supply

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INTRODUCTION

After becoming an imperial capital in AD 330, Constantinople experienced significant population growth (Cappel 1991), leading to the City's expansion across the historic peninsula (part of modern Istanbul). The second-century aqueduct of the former Byzantium soon became inadequate to fulfil the water requirements of the new City (Mango 1995); therefore a new water supply system was constructed beginning in the mid-fourth century. The arrival of the new waters was reported in historical sources in AD 373 (Donaldson 1996, p. 54), and recent studies have suggested that the total length of this fourth-century aqueduct was over 270 km (Snyder 2013). Around 30 years later, the water supply started to be extended to exploit higher springs from the north-west of Vize, with a new fifth-century aqueduct over 180 km long. The resulting water infrastructure was an intricate network of channels and bridges which continued to operate – with occasional disruptions – across the early and middle Byzantine era, until the mid-twelfth century, when it was reported to have been abandoned due to cumulative damage and decay (Crow *et al.* 2008, p. 21).

Despite its significance, the Byzantine water supply was largely ignored until Çeçen (1996) produced the first map showing the course of the channels based on interpolation from topographical maps and the fragmentary remains he observed. Further research, carried out by Crow *et al.* (2008), led to a greater appreciation of the extent of the infra-structure. Despite the archaeological work conducted so far, the physical configuration of the fourth- and fifth-century aqueducts has only been partially investigated. The course of the channels, last traced by Crow *et al.* (2008) on 10 m

contour maps of Turkish Thrace produced by the British Army in 1944, ought to be reassessed using more recent data and software.

Moreover, very little is known about the gradient of the aqueducts, which governs their hydraulic function. So far, only an average gradient of 0.6–0.7 m/km has been proposed for the entire water supply system (Çeçen 1996, p. 208; Crow *et al.* 2008, p. 121). This average slope ought to be defined in much greater detail in the light of the latest archaeological findings. It is known that the gradient profile of Roman aqueducts was typically irregular, mainly as a result of travelling through valleys, hills and plains, but possibly also due to design strategies to regulate the flow for hydraulic purposes (Hodge 2002, pp. 178–184, 216–221). Therefore a fuller understanding of Constantinople's water supply system will hugely benefit from the knowledge of local variations in slope occurring across its length.

This study discusses the integration of the latest archaeological surveying and satellite terrain data into a Geographic Information System (GIS) environment, with the aim of providing an improved description of the aqueducts' route, quantifying their length and reconstructing their gradient profile, so as to support future investigations into the hydraulic behaviour of the system.

STUDY AREA

The Byzantine water supply system of Constantinople covered a vast area extending from the historic peninsula on the Bosphorus to the north-western district of Vize in the province of Kırklareli (Figure 1). The system roughly developed on a NW–SE axis, the most upstream fifth-century aqueduct bordering the south of the Istranja mountain
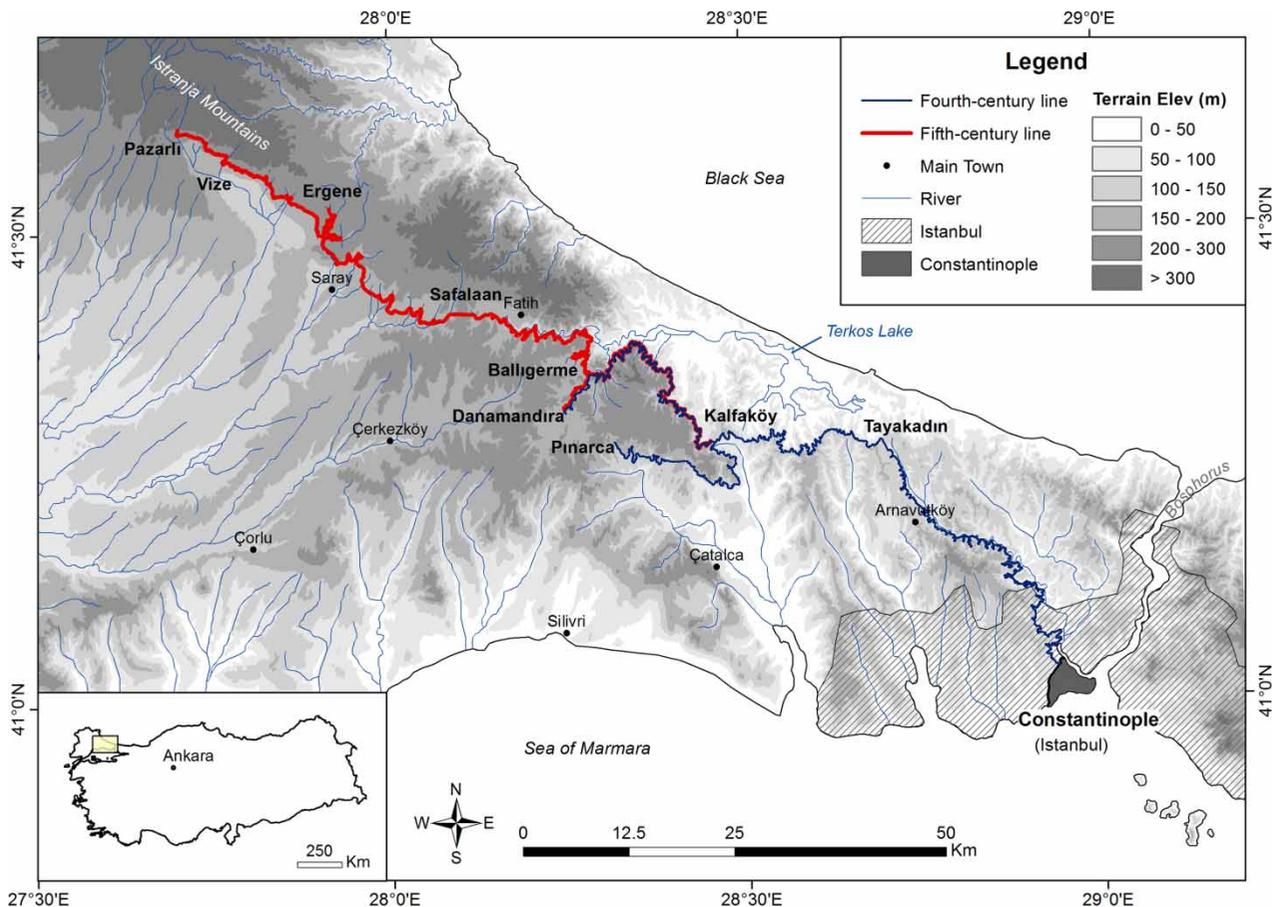

Figure 1 │ Map of the study area with topographical information, showing the Byzantine water supply lines: the fourth-century aqueduct line (in blue) and the fifth-century one (in red). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2017.062.

range, and the fourth-century channels starting at Danaman-dıra and Pınarca. Both systems run south-eastwards towards Constantinople. The farthest spring in Pazarlı lies over 120 km away from Constantinople as the crow flies, while the fourth-century springs in Danamandıra and Pınarca are around 60 km from the City in a straight line.

The study area extends into the region of Turkish Thrace which flanks the Black Sea coast, and it is characterised by densely forested hills. The elevation of the water supply system ranges between 65 m ASL, taken at the channel entrance at the land walls of Constantinople (at modern Edirnekapı), and 235 m ASL at its highest point in Pazarlı, to the north-west of Vize.

METHOD

Archaeological data sets

The archaeological studies of Çeçen (1996) and Crow *et al.* (2008) provide the most up-to-date and comprehensive documentation of the surviving remains of the Byzantine water infrastructure. Evidence of the system outside the walls of Constantinople includes remains of bridges and channels. In total, 57 channel observations have been recorded between the fourth- and fifth-century lines. The fourth-century aqueduct was found to be a narrow conduit of width around 0.60–0.65 m from the springs to Kalfaköy, while the fifth-century line started as a narrow channel on average 0.75 m wide, and widened to *c.* 1.60 m after Safalaan, around 30 km before Ballıgerme. In the furthest downstream section past Kalfaköy, there are relatively few surviving channels, mostly around 0.85 m wide; however two of these, located south of Tayakadın, were reported to be 1.20 m and 1.50 m wide (Crow *et al.* 2008, p. 85; Crow & Maktav 2009, p. 52).

In total, 93 bridges have been identified along the system, either from the fourth- or fifth-century phase (Snyder 2011); these range from small single-arch bridges to monumental structures, which mainly survive from the fifth-century expansion.

Global Positioning Systems (GPS) were used during previous surveys undertaken by Crow and his team; more information on these can be found in Maktav *et al.* (2009).

The recorded GPS points track the location of 38 bridges and 27 channel sections along the entire system.

The best preserved and most documented part of the water supply is to the east of Danamandıra. From the Ballıgerme Bridge, the fourth- and the fifth-century lines ran in parallel, but at different elevations, for a length of *c.* 51 km, gradually converging to the same level around Kalfaköy, some 140 km before the aqueduct entered Constantinople at the Theodosian Walls. Whether the two lines continued side by side from Kalfaköy to reach the City, or instead merged into a single channel has not been resolved. Given the occasional wider channel observations in the Tayakadın area and the hydraulic constriction that would result from combining the two channels into one relatively narrow conduit, we are inclined to believe that parallel channels from Kalfaköy to the City could have been a more reasonable arrangement, as was originally suggested by Crow (2007, p. 273).

Digital Elevation Model (ASTER GDEM V2)

A Digital Elevation Model (DEM) was required to reproduce the topographical features of the study area. For this, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM V2 was employed. This was released in 2011 by NASA and the Ministry of Economy, Trade, and Industry (METI) of Japan, and has a 1 arc-second grid resolution, equivalent to approximately 30 m. The vertical resolution of ASTER GDEM V2 was assessed as a root mean square error of 8.68 m against benchmark GPS points, and an absolute vertical accuracy of 17.01 m was established at the 95% confidence level (ASTER GDEM Validation Team 2011).

The ASTER tiles N41E028 and N41E029 have been mosaicked into a single scene to cover the full extent of the study area. The mosaicked original DEM was resampled to a cell resolution of 10×10 m with the creation of a Triangulated Irregular Network (TIN), which was then converted into a raster format. The latter was used as the terrain elevation model for the current study.

Data integrations and GIS analysis

A series of selected Control Points and the terrain DEM have been georeferenced using ArcGIS 10.1 (ESRI) to

trace the 3D route of the water supply system. The data integration process adopted can be synthesised into the following steps.

Identification of Control Points

A total of 22 Control Points was identified for each of the fourth- and fifth-century lines (44 in total); these have been used as benchmarks for the reconstruction of the aqueducts' route. The Control Points were selected from among the GPS survey data, where the recorded elevation was in good agreement with the topographical altitude from the DEM. In order to exclude possible sources of error, the elevation of the Control Points was assessed case by case by comparing it with the terrain data, and with photographic and textual documentation of the surviving evidence; as such, only a subset of all the GPS points available was considered sufficiently accurate to be used as benchmarks in the GIS analysis. The distribution of the Control Points along the aqueducts varies according to the availability of field data: in the best documented section between Ballıgerme and Kalfaköy, the average distance between benchmarks is in the region of 7 km; overall, the minimum distance between Control Points is in the region of 1–2 km, while the maximum ranges between 10 km and 40 km depending on the aqueduct section.

Reconstruction of the route between consecutive Control Points

For each section between two consecutive Control Points, the channel route was traced following the contour lines of the DEM. Then, given that the difference in elevation is known, the gradient of each section was calculated. Whilst there is no guarantee that the channel did, in fact, have a uniform gradient between any two given Control Point locations, the selected locations are assumed to be a reasonable guide in identifying the extent of the changes in gradient along the aqueduct lines.

Reconciliation of the line against known bridges

Accounts of existing bridges have been used, where available, to verify the proposed route of the lines. The positioning of a bridge is validated by comparing its observed dimensions, *i.e.* the maximum height and top length, against the topographical data of the surrounding terrain. A discussion of this method is presented in Case Study 2 below.

Assumption of a typical gradient for tunnels

A number of tunnels are present along the network, where the channel could have only continued by passing beneath a ridge, a feature common in Roman aqueduct systems (Hodge 2002, pp. 126–129). Whilst in some cases the tunnels' location can be clearly identified by looking at the terrain topography, little archaeological evidence is available, hence tunnel lengths and gradients had to be estimated. It is believed that tunnels were normally built with a steeper slope to reduce sedimentation problems, since the cleaning operations were more difficult in tunnels than elsewhere (Hodge 2002, p. 217). To take this into account, a slope of 1 m/km (0.001) was postulated for all the tunnels along the line, this being generally steeper than the average gradient of the channels.

The following assumptions were made prior to performing the GIS analyses. Firstly, it was postulated that the route of the water supply lines can reasonably be traced at ground level, where this represents the invert (bed) gradient of the channels. The normal course of Roman aqueducts followed the natural contours of the land, on or just below the surface, since channels were typically built in low trenches, afterwards being covered over to protect them (Hodge 2002, pp. 93–94). In such cases, it is reasonable to assume that the channel invert level is merely shifted underground by a constant height (that is the channel height, plus the vault thickness and soil covering), this being why its bed gradient would be the same as at ground level – with the exception of structures like bridges, tunnels or raised channels.

Secondly, it was assumed that the modern topographical data are a fair representation of the terrain in the fourth and fifth centuries AD, neglecting the effects of anthropic modifications and/or possible landscape modifications due to past seismic events or dissolution of limestone. In fact, it is likely that such topographical variations would not be captured within the vertical accuracy of the adopted DEM; in

addition, the use of Control Points logged in the last decades justifies the use of modern terrain data as a base map.

RESULTS

The lengths of the fourth- and fifth-century lines obtained from our analysis are shown in Table 1, compared with the figures calculated by Snyder (2013) on the basis of the route proposed by Crow *et al.* (2008). A numbering system of channels is adopted for clarity with the prefix IV representing the fourth-century sections and V the fifth-century; in each case the suffix indicates a specific sub-section of aqueduct channel.

Differences can be observed between the proposed reconstruction and the figures by Snyder (2013). The fifth-century line resulted in a similar total length at around 180 km, but variances were identified in the individual

Table 1 | Lengths of the fourth- and fifth-century systems, proposed by the authors and by Snyder (2013)

Section		Proposed length (m)	Snyder (2013) (m)
Fourth-century line: Danamandıra to Constantinople			
Danamandıra to Kalfaköy Tunnel	IV-1	66,850	N/A
Kalfaköy Tunnel to Theodosian Walls	IV-3	138,276	N/A
Total (IV-1, IV-3)		*205,126*	*227,240*
Pınarca to Kalfaköy Tunnel	IV-2	40,787	40,640
Total (IV-1, IV-2, IV-3)		**245,913**	**267,880**
Fifth-century line: Pazarlı to Kalfaköy			
Pazarlı to Ballıgerme Bridge	V-1	121,633	131,450
Ballıgerme Bridge to Kalfaköy Tunnel	V-2	51,669	51,260
Total (V-1, V-2)		*173,302*	*182,710*
Paşa Springs to Ballıgerme Tunnel	V-3	6,981	N/A
Total (V-1, V-2, V-3)		**180,283**	**182,710**
System's total length			
Fourth- and fifth-century lines merging at Kalfaköy			
Total (IV-1, IV-2, IV-3; V-1, V-2, V-3)		**426,196**	**450,590**
Fourth- and fifth-century lines as parallel systems			
Total (IV-1, IV-2, IV-3; V-1, V-2, V-3, IV-3)		**564,472**	N/A

sections. On the other hand, the proposed fourth-century line is around 22 km shorter than the earlier study: this discrepancy is mainly due to the different route traced for the furthest downstream section IV-3 between the Kalfaköy Tunnel and Constantinople. In fact, this area has yielded little archaeological information, so both the proposed and the previous reconstruction should be considered mostly hypothetical. However, it should be noted that the previous route might have been subject to a larger error due to an approximate interpolation of 10 m contours used by Crow *et al.* (2008), while our proposed distance was obtained from a systematic analysis on a more detailed terrain map. Since the elevation of this line was unchanged, the additional 22 km of channel from Snyder (2013) would have a major impact on the gradient of section IV-3, which would be reduced even further: this would be critical for the system capacity because section IV-3 has the shallowest recorded gradient even for our proposed shorter distance, as explained below.

Our proposed total lengths of the Byzantine water supply system are 245.9 km and 180.3 km for the fourth- and fifth-century lines respectively. This indicates that the entire system would have been 426.2 km long if the two lines merged at Kalfaköy, which is 24.4 km shorter than the previous estimate. However, the consideration of a separate, parallel fifth-century channel in section IV-3 would add a further 138.3 km, reaching a total figure of 564.5 km.

The gradients of the aqueduct lines have been studied for the first time through our GIS reconstruction. A breakdown of the estimated gradient for each line is shown in Tables 2 and 3, where a further suffix is used in our numbering system to describe each channel segment in sequence from upstream to downstream. The calculation of average gradient for each aqueduct section in the tables does not include the most upstream segment near the springs (marked with an asterisk), being typically steeper than the rest of the aqueduct channels. It should be stressed that, due to the difficulty in identifying the exact elevation at the springs, gradients for these segments should be regarded as merely indicative; the proposed values may be refined if new survey campaigns are conducted. Nevertheless, from the available evidence it is possible to conclude that the intake channels had a significantly steeper gradient than the downstream channels.

Table 2 | Gradient of the fourth-century system

Section	Elevation (m)	Distance (m)	Gradient
Section IV-1: Danamandıra Springs to Kalfaköy Tunnel			
IV-1-1 to IV-1-2 (*)	171–154	3,318	0.0051
IV-1-2 to IV-1-3	154–150	5,645	0.0007
IV-1-3 to IV-1-4	150–146	5,285	0.0008
IV-1-4 to IV-1-5	146–133	17,178	0.0008
IV-1-5 to IV-1-6	133–128	8,945	0.0006
IV-1-6 to IV-1-7	128–123	10,402	0.0005
IV-1-7 to IV-1-8	123–121	4,283	0.0005
IV-1-8 to IV-1-9	121–114.5	11,273	0.0006
IV-1-9 to IV-1-10	114.5–114	520	0.0010
Total/Average (*)	**171–114**	**66,850**	**0.0006**
Section IV-2: Pınarca Springs to Kalfaköy Tunnel			
IV-2-1 to IV-2-2	152–144	6,486	0.0012
IV-2-2 to IV-2-3	144–135	9,530	0.0009
IV-2-3 to IV-2-4	135–133	2,005	0.0010
IV-2-4 to IV-2-5	133–131	2,178	0.0009
IV-2-5 to IV-1-10	131–114	20,587	0.0008
Total/Average	**152–114**	**40,787**	**0.0009**
Section IV-3: Kalfaköy Tunnel to Constantinople Walls			
IV-1-10 to IV-3-1	114–111	5,608	0.0005
IV-3-1 to IV-3-2	111–95	41,253	0.0004
IV-3-2 to IV-3-3	95–94	1,361	0.0007
IV-3-3 to IV-3-4	94–90	11,735	0.0003
IV-3-4 to IV-3-5	90–80	30,425	0.0003
IV-3-5 to IV-3-6	80–72	25,266	0.0003
IV-3-6 to IV-3-7	72–65.5	22,629	0.0003
Total/Average	**114–65.5**	**138,276**	**0.0004**

Note: the average gradient of Section IV-1 does not include the steep intake segment marked with an asterisk.

Table 3 | Gradient of the fifth-century system

Section	Elevation (m)	Distance (m)	Gradient
Section V-1: Pazarlı Springs to Ballıgerme Bridge			
V-1-1 to V-1-2 (*)	235–232	682	0.0044
V-1-2 to V-1-3	232–225	7,176	0.0010
V-1-3 to V-1-4	225–218	8,669	0.0008
V-1-4 to V-1-5	218–211	6,150	0.0011
Ergene tributary (*)	216–197	941	0.0200
V-1-5 to V-1-6	211–196	14,091	0.0011
V-1-6 to V-1-7	196–192	4,034	0.0010
V-1-7 to V-1-8	192–181	12,498	0.0009
V-1-8 to V-1-9	181–171	21,357	0.0005
V-1-9 to V-1-10	171–164	7,896	0.0009
V-1-10 to V-1-11	164–160	4,577	0.0009
V-1-11 to V-1-12	160–147	21,196	0.0006
V-1-12 to V-1-13	147–142	9,106	0.0005
V-1-13 to V-1-14	142–141	1,558	0.0006
V-1-14 to V-2-1	141–140	1,702	0.0006
Total/Average (*)	**235–140**	**121,633**	**0.0008**
Section V-2: Ballıgerme Bridge to Kalfaköy Tunnel			
V-2-1 to V-2-2	140–138	4,502	0.0004
V-2-2 to V-2-3	138–135	6,529	0.0005
V-2-3 to V-2-4	135–128	15,248	0.0005
V-2-4 to V-2-5	128–124	9,214	0.0004
V-2-5 to V-2-6	124–121	5,998	0.0005
V-2-6 to IV-1-9	121–114.5	10,178	0.0006
Total/Average	**140–114.5**	**51,669**	**0.0005**
Section V-3: Paşa Springs to Ballıgerme Tunnel			
V-3-1 to V-1-14	166–141	6,981	0.0036

Note: the average gradient of Section V-1 does not include the steep intake segments marked with an asterisk.

As Table 2 indicates, the gradient of the fourth-century line varies quite significantly across the three sections, going from average values of *c.*0.6 m/km in IV-1 and 0.9 m/km in IV-2, and becoming much flatter in the downstream section IV-3, mostly below 0.4 m/km. In this section, the shallowest slope is identified downstream of the Tayakadın tunnel (IV-3-2 to IV-3-3), at just 0.3 m/km for the last 90 km approaching the City. Steeper slopes can be identified in the first segments of sections IV-1 and IV-2, respectively, at the water intakes from the springs of Danamandıra and Pınarca, with a maximum estimated figure of *c.* 5 m/km.

Table 3 illustrates the gradient of the fifth-century line: similarly to the fourth-century line, the gradient is found to decrease as the channel continues downhill. In particular, the gradient of the furthest upstream section V-1 is on average 0.8 m/km, if neglecting the steeper intake stretch, while the following aqueduct section (V-2) becomes much flatter, at an average slope of 0.5 m/km. The conduits in the vicinity of the springs would have had a steeper gradient, around 4.4 m/km at Pazarlı (V-1-1 to V-1-2) and 3.6 m/km at the Paşa springs (V-3), and possibly up to 20 m/km for the short tributary from the Ergene springs. It should be

highlighted that archaeological evidence for the Ergene and the Paşa channels is particularly scarce, therefore the proposed figures may not be a close representation of the actual gradient or length of the conduits.

Overall, it can be concluded that the gradient of the system was mostly below a figure of 1 m/km, with the exception of short steep stretches corresponding to the spring intake conduits. These account for less than 10% of the total length of the system, and their gradient is mainly in the region of 5 m/km. For both aqueduct lines, the average gradient has shown a clear tendency to decrease from upstream to downstream, going from *c.*1 m/km to 0.4 m/km closer to the City.

Case study 1: the Safalaan tunnel

The spatial analyses performed in ArcGIS have supported the identification of tunnels along the system. This case study examines the fifth-century tunnel located to the south of Safalaan village. Despite the fact that no archaeological evidence has yet been found to document either an entrance or an exit, the need for this tunnel is confirmed by the topography of the site and the known channel observations. Remains of the channel have been located on the west and east side of the Safalaan ridge, respectively, at an elevation of 171 m (Control Point V-1-9) and 164 m (Control Point V-1-10). It is evident that the channel could only have continued by tunnelling through the ridge, crossing from the Ergene watershed into the Binkılıç Deresi basin, since it would be extremely disadvantageous, as well as hydraulically unfeasible, to follow the contours on the surface on a different route.

Hypotheses have been made by the authors on the possible route of the Safalaan tunnel, as shown in Figure 2. As stated above, a gradient of 1 m/km was assumed for every tunnel along the system. Using this slope, the route of the
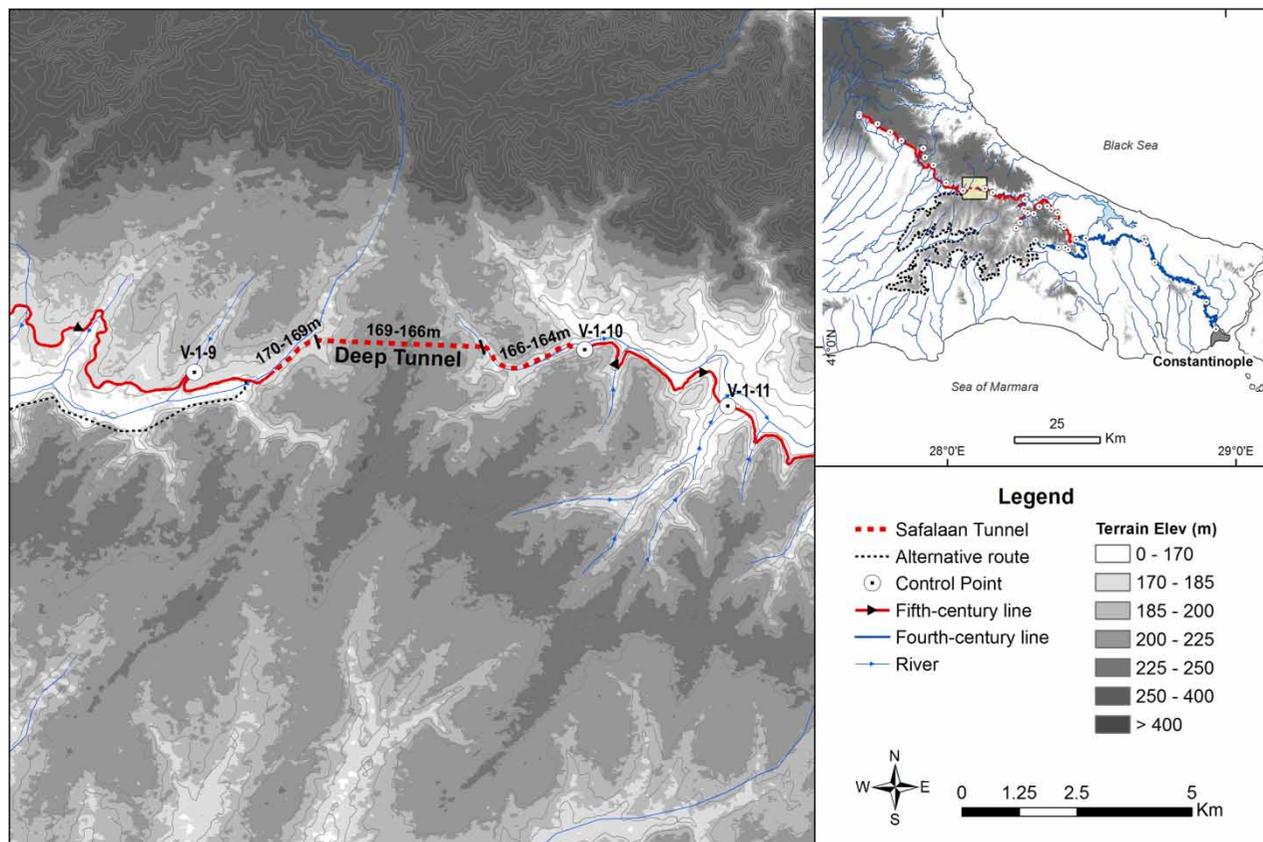

Figure 2 | Topographical map with indication of the possible route of the Safalaan tunnel and the alternative route that has been disproved.

tunnel was estimated by minimising its length and the consequent requirement for excavation. We suggest that the channel could have been built in a deeper trench (a few metres below the ground) to follow the route suggested by the contours on both sides of the ridge for a length of *c.* 1.1 km upstream of the tunnel (from elevation 170 to 169 m) and of *c.* 2 km downstream (from 166 to 164 m). In such a case, the main tunnel required to cross the crest of the ridge would have been *c.* 2.7 km long and between 10 m and 50 m deep. In the authors' view, this solution would have probably been more practical than building the tunnel as a straight line regardless of the topography, which would have required a continuous tunnel *c.*5 km long. However, due to the lack of archaeological evidence for the identification of the tunnel route, one cannot exclude that this tunnel was actually built as a straight line, either as a continuous bore or by using a multi-shaft approach.

Case study 2: bridge at Manganez Dere valley

This case study discusses the positioning of an aqueduct bridge by examining the Manganez Dere Bridge (K9 from Çeçen's notation, where K stands for *köprü*, bridge). This is located on the fifth-century line, around 5 km downstream of the Safalaan tunnel (see Case Study 1). The channel is known to approach the Manganez Dere valley from the north-west direction at an elevation of 161 m. It is on the east side of the valley that the first observation of a wider channel was encountered along the line, corresponding to Control Point V-1-11 (Figure 3). The fifth-century bridge has almost completely vanished, except for remains of the west abutment. The size of this, around 26 m long and up to 2 m high, suggests the existence of a monumental bridge, which was previously estimated as 80 m long and *c.*10 m high (Crow *et al.* 2008, pp. 42-43). However, more
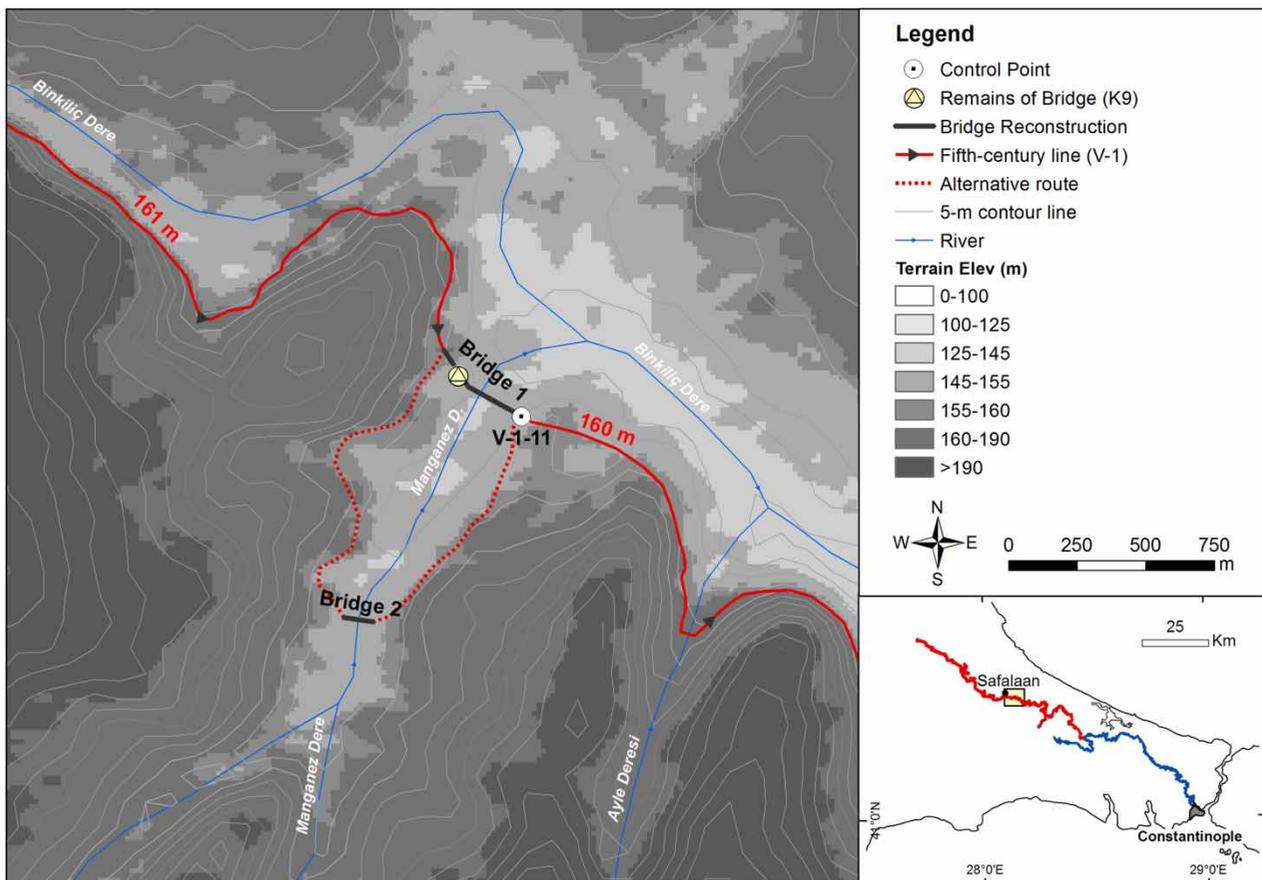

Figure 3 │ Topographical map of the Manganez Dere valley with reconstruction of the bridge (K9).

detailed analyses on the topography of the valley and the necessary elevation of the channel indicate that the combined length of the bridge, together with any approach embankments, would have needed to be over 250 m to cross the valley at the considered location (marked as 'Bridge 1' in Figure 3).

Traces of a channel from the south-west direction, identified as a tributary channel, were recorded by Crow *et al.* (2008, p. 43). An alternative interpretation is that these remains represent the route taken by the main aqueduct line, either at first construction or in a later period following repairs. This alternative route would follow the contours further to the south and cross the stream where a shorter bridge, *c.*80 m long, would have been sufficient (see 'Bridge 2' in Figure 3).

DISCUSSION

The proposed GIS-based reconstruction offers a validation for the figures suggested by previous works regarding the length of the water supply system of Constantinople (Crow *et al.* 2008; Snyder 2011, 2013). Despite being largely neglected in the accounts of Roman aqueducts, this infrastructure is remarkable. Our analysis shows the total length of the aqueduct system to be around 426 km with a junction between the fifth-century and fourth-century lines at Kalfaköy, and 138 km longer than this if the two aqueducts continued separately further downstream. This would result in a total length of *c.*565 km which, combined with the estimated 47 km of the second-century line (Snyder 2013, p. 199), would amount to *c.*611 km. In such a case, the aqueducts of Constantinople would have been much longer than those of any other ancient water supply, including that of Rome itself, which was built over seven centuries and had a total length of 502 km amongst 11 separate routes (Hodge 2002, p. 347). Moreover, our systematic assessment of the aqueduct gradient has for the first time verified the feasibility of the whole water supply system by confirming that it would have flowed downhill with a shallow gradient mostly below 1 m/km, except for short steeper stretches close to the water sources.

CONCLUSIONS

An assessment of the route and the gradient of the Byzantine aqueduct system of Constantinople was achieved through the integration of available archaeological and GPS data and modern satellite contours. The results have confirmed most of the route proposed by previous works, and demonstrated that the total length of channels could have been in the region of 426 km, and possibly around 565 km when considering a dual channel all the way to the City. These figures are far longer than any other water supply known from the Roman world. The gradient profile of the aqueduct channels has been reconstructed for the very first time, and indicates that the bed slope varied along the length of the system, being steepest at around 5 m/km near the spring sources, and flattest at around 0.4 m/km in the most downstream section nearest the City. This study significantly expands prior work on the Byzantine water supply system, by proposing a robust characterisation of length and gradient, and providing the framework for future studies to assess its hydraulic function.

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