Northumbria Research Link

The Valens Aqueduct of Constantinople: Hydrology and Hydraulics

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Introduction and background

The modern visitor to Istanbul sees a 971 m long aqueduct bridge commonly referred to as the *Valens Aqueduct*. In fact this bridge, impressive though it is, is just one small part of a water supply system stretching hundreds of kilometres into the Thracian forest, bringing water to the city that was the capital of the Roman Empire from AD 330. Contemporary sources attest to the lack of water, Themistius *Oratio XIII* noting the city *"afficted with thirst and drought and not far from vanishing…"* In response to what was apparently a seasonal problem, major aqueduct construction took place from around 340 to 373 (the 4th Century line), with a further very significant extension around fifty years later (the 5th Century line) (Crow et al. 2008). Despite its length and importance, the system was very little considered by classical archaeologists until (Çeçen 1996) and (Crow et al. 2008).

This latter study gave rise to a solid understanding of the arrangement of the system, which is shown in Figure 1. The 4th century line has two main sources, at Danamandıra (where the Kaynarca and Papu springs were adjacent) and at Pinarca, with the two branches merging into a single channel near Kalfaköy. This system was approximately 250 km long; the sources at Danamandıra were 171 m above sea level (asl) with the walls of Constantinople being 65 masl. The 5th century extension took flow from springs at Pazarlı, 240 masl, via a branches at Ergene and Binkılıç and a long branch at Paşa, also near Danamandıra. The 5th century system was therefore at least 180 km of additional aqueduct channel. This ran in parallel with the 4th century channel, at a lower elevation, in the central section, and may have either merged into the earlier line near Kalfaköy or continued as a completely separate channel to the city. There is insufficient archaeology in the region close to the city to determine which of these eventualities was the case, much of this area having been destroyed by more recent urban development of one of the world's megacities. The lengths of the channels easily justify (Çeçen 1996)'s epithet of 'The Longest Roman Water Supply Line'. The channels were all of masonry, of a rectangular form with a vaulted cover; the walls up to the springing of the vault being lined with hydraulic mortar. Most channels were narrow, of width around 0.65 m and height to the top of the vertical wall (the vault springing) of around 1 m[1]. However the 5th century channel from Safalaan to Kalfaköy was wide, 1.6 m in width and around 1.7 m high to the top of the vertical wall (Crow et al. 2008).

Outside Istanbul, the system is still little conserved and visited, much of it lying in relatively inaccessible areas; however there are remains of over 90 bridges and many sections of channel,

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[1] The total height to the apex of the vault was of course higher than this.

including the spectacular multi-tiered bridges at Kurşunlugerme and Kumarlıdere (Figure 2). Whilst the archaeology is now quite well understood, there has not previously been any investigation into the function of the system as a piece of water engineering. The research presented here is intended to plug that gap.
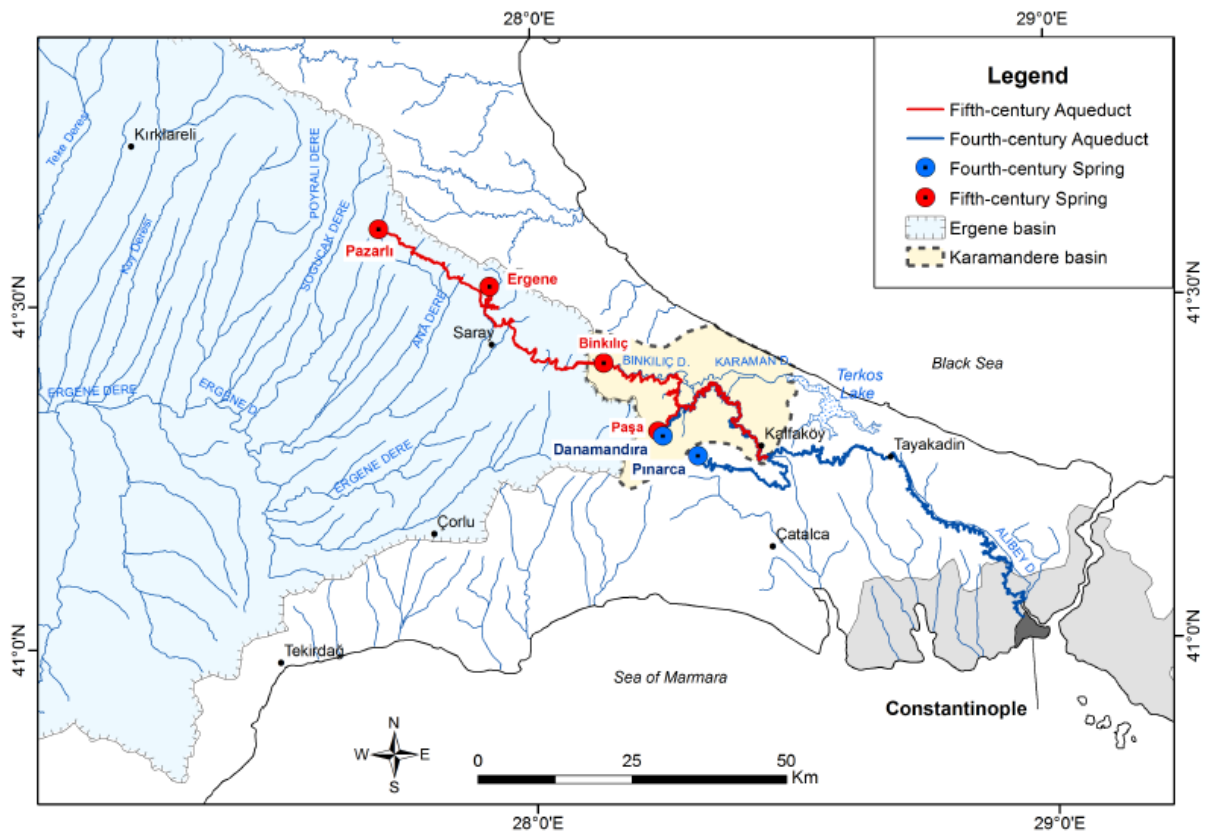

Figure 1: Plan of the Valens aqueduct system showing 4th and 5th century lines and locations of main spring sources and watersheds

(a)

(b)

Figure 2: Aqueduct bridges at (a) Kurşunlugerme and (b) Kumarlıdere

Aims

The aim of this research was to investigate the hydrology and hydraulics of the Valens aqueduct system, and specifically to understand the hydraulic properties of the channels, such as their cross-section and slope, to study the amount of water available and capable of entering the aqueduct system, to examine the hydraulics of the aqueduct and so determine the amount of water that might have been delivered to the city of Constantinople, and to draw conclusions as to the likely configuration of the system where archaeology has not yet been able to clarify this.

Hydraulic properties

58 channel observations have been recorded for the entire system of 4th and 5th century lines. The 4th century channel was found to be a narrow conduit of width around 0.65 m from the springs to Kalfaköy, while the 5th century channel started as a narrow channel around 0.70 m wide, and widened to 1.60 m after Safalaan. In the section downstream of 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, Crow et al. 2009). In addition, field surveys gave GPS locations for 38 bridges and 27 channel sections (Maktav et al. 2009).

A digital elevation model of the aqueduct catchment was created, based on the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM V2, released by NASA in 2011. This has a horizontal resolution of around 30 m and a vertical root mean squared error of 8.68 m against known GPS benchmarks. This model was imported into ArcGIS and combined with the GPS points of the aqueduct, with lengths in between the surveyed points being traced along contours at a constant slope. Adjustments were made to account for the known length of bridges spanning valleys, whilst the three tunnels on the system, where the channels pass under ridges, were assumed to have a steeper slope of 1 m/km according to (Hodge 2002) p. 271.

From this analysis, total lengths of the system are 245.9 km and 179.4 km for the 4th and 5th century lines respectively; the whole system would have been around 425 km long with the channels merging at Kalfaköy; a separate, parallel 5th century channel downstream of Kalfaköy would add a further 138 km of construction.

The GIS study also allowed calculation of the channel gradients. That of the 4th century line varies quite significantly, from around 0.7 m/km from Kaynarca to Kalfaköy and 1.0 m/km from Pinarca to Kalfaköy, to much flatter in the most downstream section after Kalfaköy, below 0.4 m/km. Steeper slopes are identified in the most upstream sections, close to the springs, with a maximum slope of 5.1 m/km. In the 5th century line, the gradient is also found to decrease as the channel continues downhill. In particular, the gradient of the most upstream section is on average 0.8 m/km, if neglecting the steeper stretch at the intake, while the following aqueduct section becomes much flatter, at 0.5 m/km. Similarly to the 4th century line, the conduits in the vicinity of the springs have a steeper gradient, around 4 m/km at Pazarlı.

A plot of the slope of the system is shown in Figure 3, and the GIS study and channel geometry is fully detailed in (Ruggeri 2018) chapter 5 and appendix A.
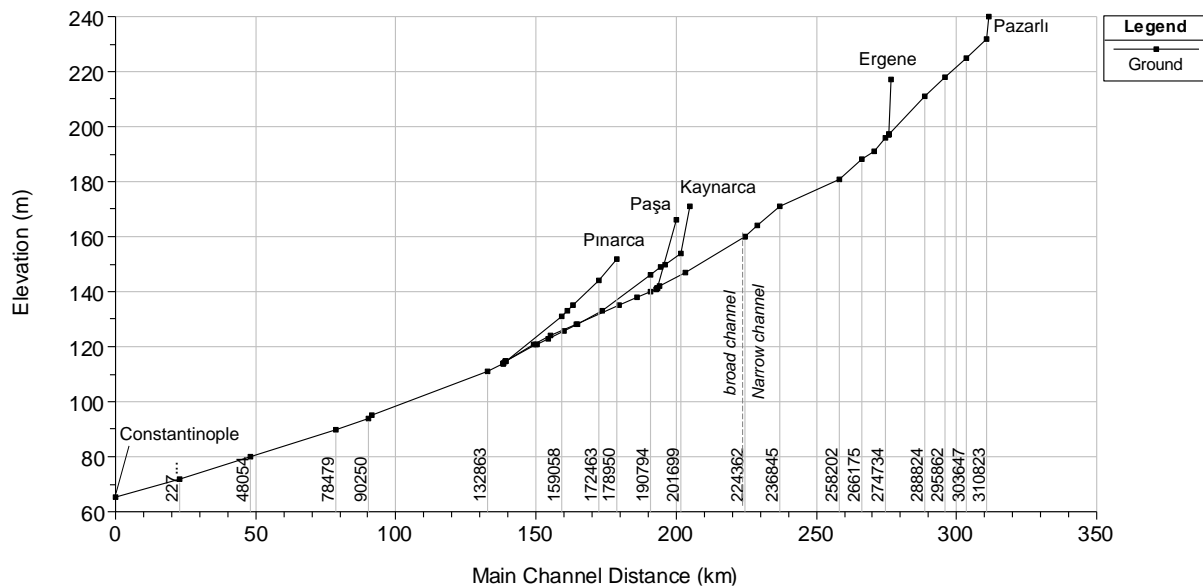
Figure 3: The gradient profile of the Valens aqueduct system (Crapper et al. 2016)

The final component of hydraulic properties is the friction factor. No further research was carried out in regard to this; in all the analyses carried out, Manning's equation was used, with a friction coefficient of 0.014, corresponding to plaster-lined masonry, which was common for Roman aqueducts and observed by us in several of the surviving channels, for example at Pınarca and at Kumarlıdere. This value of Manning's 'n' follows the practice of (Keenan-Jones et al. 2015) and (Motta et al. 2017) for Roman aqueducts.

Water available for use

Whilst there have been some studies on the possible water-carrying capacity of Roman aqueducts (for example (Keenan-Jones et al. 2015) and (Motta et al. 2017) previously cited). A few, including (Bobée et al. 2011) and (Keenan-Jones 2013) have considered the amount of water available to flow into the aqueducts at various seasons, including some consideration of possible variations between ancient and modern times. Given the size and complexity of the Valens aqueduct catchment, the amount of water obtainable, or in modern terms, the hydrology of the catchment, must have been a serious consideration for its Roman designers.

The catchments of Karamandere and Ergene, in which the relevant springs are located is karst (Bono et al. 2001), i.e. a landscape formed by the dissolution of carbonate rocks, typically limestone. Such watersheds are hydraulically complex, as each has a unique arrangement of fissures and cavities. The underground links between these often result in the hydrological catchment being bigger than the topographical catchment that would be defined from the ground slope at the surface, and there is no general model available to predict the runoff of such a catchment without individual site data relating rainfall to runoff and spring flow. In particular, the time response between rainfall and runoff can vary from very slow to very rapid. A full discussion of karst hydrology relating to the Valens aqueduct system is contained in (Ruggeri 2018), Chapter 6.

Modern site data for the region is limited, and site data contemporary with the design and construction of the aqueduct is of course unavailable. Further, although karst changes slowly on average, sudden changes, due, for example to the collapse of a cave, are possible and there is no way of telling if such events have occurred since the aqueduct was commissioned.

Hydrological data

Two modern sources of hydrological data were available, a report from DSI, the Turkish government agency responsible for hydrology (DSI 1977) and a further range of data from the same institution communicated privately. (DSI 1977) focuses on the NE corner of the Ergene catchment, encompassing the springs that would have fed the 5th century extension of the aqueduct at Pazarlı and Ergene. As well as monthly average rainfall, it includes monthly average flow for the major springs, and yearly average for the minor ones, over the period 1969 to 1973. Combining GIS and geo-referencing with the information in (DSI 1977), it is concluded that the spring reported as Pazarlı Ayazma may have been that providing the major source of water at the upstream end of the 5th century system. Another, much smaller spring, named Çakilli Ergenekorusu Kaynağı, is recorded near Ergene and could have fed the aqueduct tributary there.

The second source of data covers the period 1976 to 2016 (with not all years present in every record) with much more wide-ranging information from several weather stations and stream gauging stations, but it does not include spring flow data, and none of the stream gauging stations are particularly close to potential aqueduct springs, but are all further downstream.

Historic climate

Since all the hydrological data was relatively modern, it was important to consider whether the climate had changed significantly since the time of the Valens aqueduct's design. Macrophysical Climate Modelling (MCM) (Bryson et al. 2007) was employed to determine likely changes in monthly rainfall, maximum, minimum and mean temperatures between the period AD 350-750 when the Valens aqueduct was in use, and modern times. Eight weather stations were used, Kırkareli, Çorlu, Bahceköy, Alpullu, Florya, Kumköy, Yalova and Tekirdağ. Of these, only the first two at 232 and 173 masl were high enough for the rainfall recorded there to enter the aqueduct. Bahceköy is at 130 masl and the rest all below 40 masl. The results of the MCM process show some higher summer rainfall peaks in the 350-750 period, but the stations most relevant to the aqueduct, Kırkareli and Çorlu, show very little difference from modern rainfall and temperature pattens (Figure 3). There is clearly no absolute way of validating these results, but it is concluded that modern weather data is a reasonable proxy for that that would have been obtainable at the time of the Valens aqueduct's construction and use.

Spring Flow

The monthly discharge records for the Pazarlı Ayazma spring from (DSI 1977) were used to define a typical spring discharge hydrograph to assist in understanding the amount of water available to the Valens aqueduct system. Three annual hydrographs were produced, one from the minimum flow in each month, 1969-73, one for the average flow in each month and one for the maximum flow for each month over those years of record. Results of this analysis for the spring flow are shown in Figure 5. The spring flows at Ergene were similarly reconstructed for low, average and high flow scenarios. However, as this was a classified as a minor spring in (DSI 1977), only annual average flows were available. It was therefore assumed that its montly variations were proprionately similar to those at the larger spring. Reconstructed flows for Ergene are also shown in Figure 5.

As a sense-check on these data, more recent stream gauging stations were used. This data included stations D01A031, in the next valley from Pazarlı and D01A033 close to Ergene. Using a GIS analysis, a comparison was made between the topographical catchment upstream of these stations and that at the spring locations feeding the aqueduct, giving a possible proportionate relationship between the monthly flows measured at the stream gauging stations and those at the springs, these being the main feeders for all the rivers in the area. For Pazarlı, the spring topographical catchment was 0.19

of that for river station D01A031 and for Ergene it was 0.02 that of D01A033. Applying this proportion to the measured river flows gave comparable results (Figure 5). In each case the peak spring flow is in the January to April period and the monthly flows are of a similar order of magnitude.
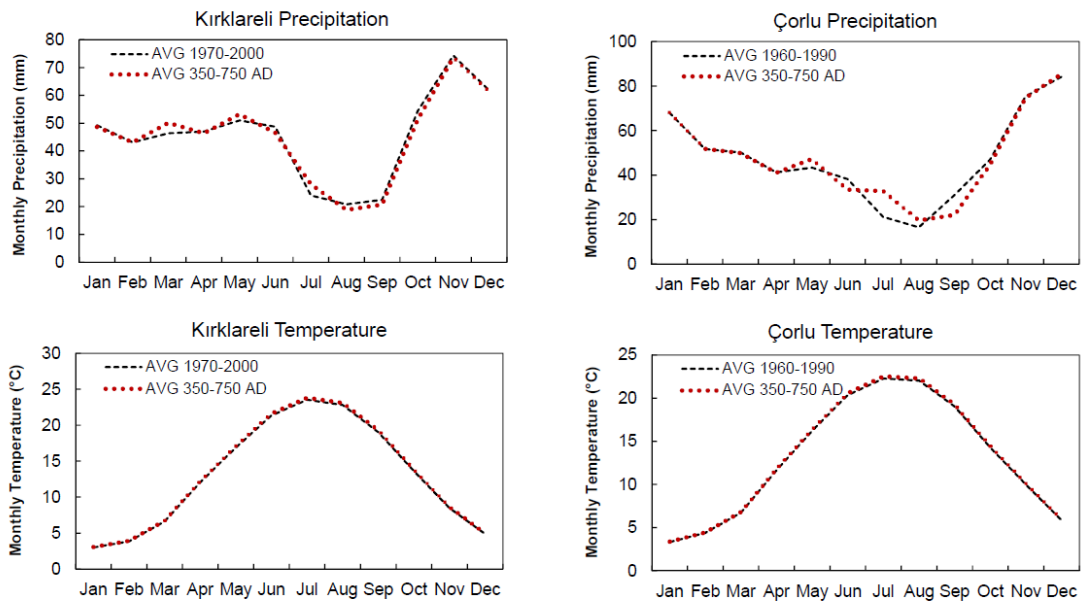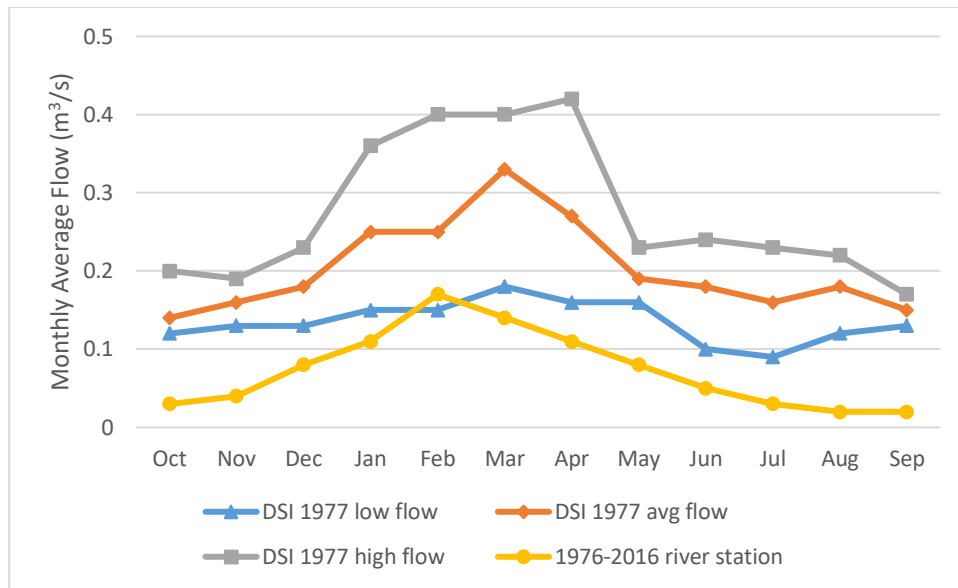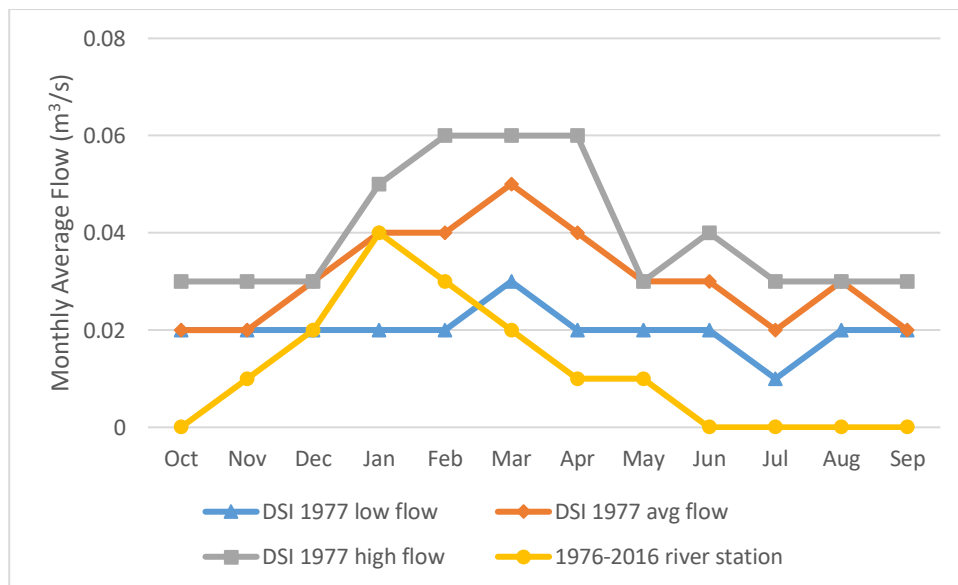

Figure 4: Results of Macrophysical Climate Modelling (MCM) for Kırkareli and Çorlu weather stations showng difference in montly average temperature and rainfall between AD350-750 and modern times (Ruggeri 2018)

(a) Pazarlı Ayazama

(b) Ergene

Figure 5: Reconstructed hydrographs for springs for low, average and high flow scenarios and cross-check with river station data, (a) at Pazarlı Ayazma and (b) at Ergene

Intake arrangements

The amount of water at the spring is an important consideration. However, there is no *a priori* reason to assume that all water emerging from a spring would enter the aqueduct system. The Roman designers may have been conscious of the need for spring water in the immediate locality of the spring; they would also have had to design and construct an intake structure.

Whilst it was not possible to undertake an archaeological investigation or take measurements of any kind, the intake arrangements at Pazarlı and Pinarca all survive to some extent and can be readily examined by any visitor. The author was thus able to visually inspect them from an engineering perspective. At Pazarlı, the aqueduct has clearly been adapted for use in more recent times, up to the 20th century, and the situation is a natural stream, fed by the spring, with a weir and sluice

arrangement leading to the aqueduct channel (Figure 6 a and b). Here the aqueduct channel was identifiable in the undergrowth towards the back of Figure 6 a.

At Pinarca, there are three springs with separate intakes. One is immediately outside a cave, where the aqueduct channel (Figure 6 c) leads off at the side of the natural stream emerging from the cave, and fallen masonry with clamp notches (Figure 6 d), in the stream bed suggests that a weir controlled the stream, diverting flow into the aqueduct, much like the altered system observed at Pazarlı. The second intake at Pinarca is a deep, well-like cave fed by a spring at its base, and feeding at least two aqueduct channels at different levels, the higher of which appears to be an overflow leading to the stream fed by the spring at the first intake (Figure 6e). The third intake here is another cave with a weir-like wall constructed over the lower half of its entrance. At the base of this wall, in the centre, is the entrance to the aqueduct channel (Figure 6f). Flows too high to enter the aqueduct would build up behind the weir, inside the cave, eventually overflowing into a natural stream.

All these surviving details suggest that the intake structure of choice for the aqueduct system may have been a weir intended to divert spring flow from its natural channel, but with some provision for continuation flow, at least in high flow situations. This makes sense, since a covered aqueduct channel would clearly have a maximum capacity, and failure to provide for overflow of excess spring water would possibly have had detrimental consequences.

Another feature of the intakes to the aqueduct system is their relative steepness. For example, between Pazarlı and Safalaan 76 km length of 5th century channel, the GIS analysis has shown an average slope of just below 1 m/km. However, closer to the intakes it is much steeper, 4 m/km at Pazarlı and perhaps up to 20 m/km at Ergene. This steepening near the intake appears to be the case for the other intakes across the whole aqueduct system (Ruggeri et al. 2016) and may thus be considered a design feature. It may have been intended to speed water away from the intake quickly, since the steeper channel means that the absolute capacity of the intake region is greater than that of the channel immediately downstream, or it may have been a result of conservative surveying practices, ensuring the main aqueduct channel was below the spring elevation and using the most upstream section to complete the connection as necessary.

On balance it is concluded that the aqueduct intakes demonstrate evidence of deliberate design, and had an arrangement that would divert flow into the channel without a local constraint on the channel, but would provide for some overflow, at least at high flows.

Remaining intakes – channel conveyance analysis

In order to fully understand the aqueduct system, it is clearly necessary to have an idea of the water entering it at every intake, not just at the 5th century springs for which data was recoverable from (DSI 1977). However none of the available data gave any real guidance as to quantities of water available at the remaining springs identifed by (Crow et al. 2008), i.e. at Binkılıç and Paşa on the 5th century line and at Danamandıra and Pinarca on the 4th century line.

To provide inflow information for subsequent modelling, flows at these locations were estimated by analyzing the proportion of total channel conveyance used at Pazarlı and Ergene, where spring flow information was available, and assuming the remaining intakes were designed to give a similar utilization of total channel conveyance, i.e. assuming consistent design approach across all the intakes and channels.

Figure 6: Modern weir sluice arrangement near intake at Pazarlı (a and b), the inlet to the aqueduct channel being hidden in the undergrowth behind Dr Ruggeri in (a); and springs at Pinarca showing aqueduct channel (a) and fallen masonry that may have been a weir of Roman construction (d) at the first spring; well-preserved channel at the second spring (e); and channel (with a modern water pipe fed through it) at base of weir at the third spring (f)

The analysis was carried out by means of the industry standard river modelling package HEC-RAS, (Brunner 2010). This applications software solves the well known St Venant Equations describing one-dimensional flow in open channels and provides many features to allow various hydraulic structures and situations to be simulated. It is appropriate for modelling Roman aqueduct channels which were designed to flow with a free surface (the vault at the top of the masonry channels being well above the water surface) and under gravity. Full details of the data used for the analysis and the complete results are included in (Ruggeri 2018) chapter 7 and Appendix D.

Steady-flow analyses were run for the the 5th century channel from Pazarlı to Safalaan, using the low, average and high flow scenarios previously defined (Figure 5) and assuming the entire flow of

the springs entered the aqueduct. Channel slope and length was from the GIS analysis, cross-section dimensions were taken from the observations of (Crow et al. 2008), and the frictional characteristics of the channels were kept constant with a Manning's n value of 0.014 as discussed earlier. Conveyance ratio was determined as the ratio of the cross-section shown to be taken up by the flow, divided by the total available cross-section of channel.

The critical section of the simulated section of channel, where conveyance ratios were highest, meaning the channel was most full, was between around 237 and 248 km from the city walls, upstream of the Safalaan tunnel. Here, for the high flow scenario, flow exceeded the maximum channel capacity. At the intakes, where the channel was steeper, the conveyance ratio was always lower, as expected. A typical performance for the section of channel was calculated by averaging the modelled conveyance ratio along the length of the channel, excluding the steeper intake sections. A further intake conveyance ratio was calculated for the Pazarlı intake only, corresponding to the most detailed hydrograph derived from the (DSI 1977) report. These results are shown in Figure 7.
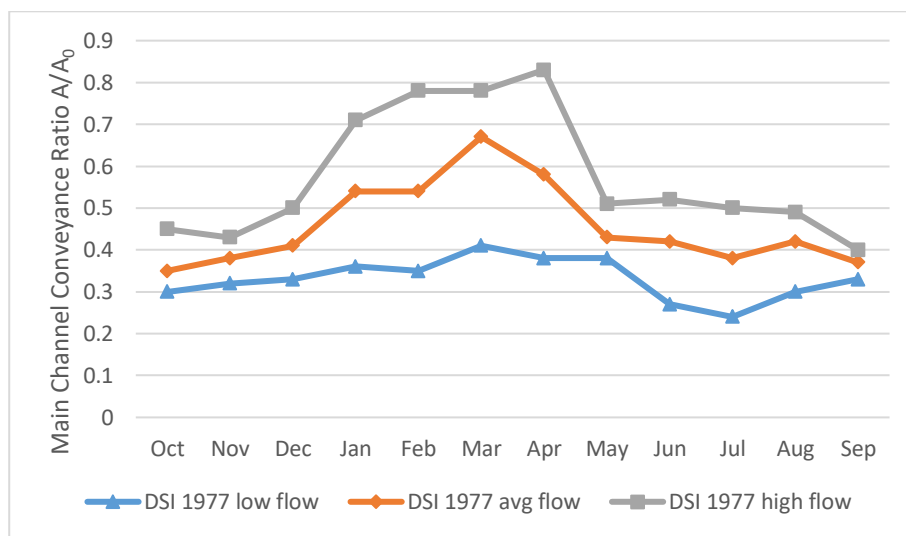
(a)   main channel from Pazarlı to Safalaan
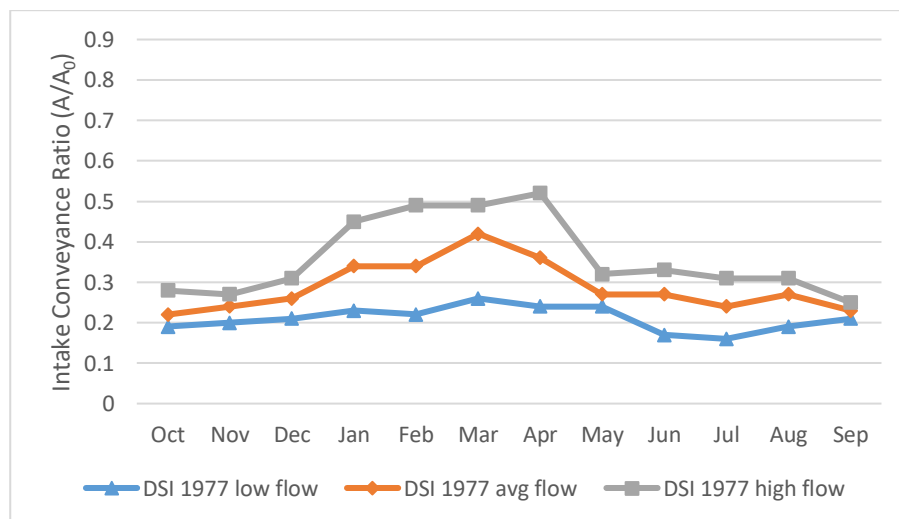
(b) Pazarlı intake channel

Figure 7: Monthly conveyance ratio for typical and intake scenarios for 5th century channel where spring data is available from DSI report for (a) the main channel from Pazarlı to Safalaan and (b) the Pazarlı intake channel. A is the utilized cross-section of channel; A0 is the total cross-section available

The conveyance ratios in Figure 7 were used as a basis to estimate flows at the remaining springs, imposing the conveyance ratio on the relevant channel section. The 4th century channels from Danamandıra and Pinarca have been reasonably well documented, and are of comparable size with the Pazarlı to Safalaan section of the 5th century line; therefore the typical convenance ratios were used here, in effect assuming that all these channels would behave similarly along much of their length. At Binkılıç and Paşa, there is no record of archaeology, so no conclusion can be made about the behaviour of a long length of channel. It was therefore surmised that these springs would feed via an intake designed with a similar objective to the Pazarlı intake, and the conveyance ratio for that intake channel was therefore taken as the design ratio.

The inflow estimation was carried out by repeated HEC-RAS steady flow simulation, varying the inflow until the required conveyance ratio was obtained. The resulting conveyance ratios are shown in Figure 8.

Further steady flow HEC-RAS analyses were carried out to determine the maximum capacity of the intakes at each location. In every case, the limiting factor was not the steeper intake channel itself, but the restriction where the channel slope reduced somewhat downstream. The intake maximum capacities are shown in Table 1, and in each case it is apparent that the monthly average flow determined is always well below the intake capacity.

The range of assumptions made in coming to these figures will be apparent to the reader; clearly in coming to a view regarding flows that took place over 1600 years ago, assumptions are always going to be necessary. According to MCM, the climate of modern times is considered to be a reasonable proxy for that at the time the Valens aqueduct system was constructed; the (DSI 1977) data for the at springs of Pazarlı Ayazma and Çakilli Ergenekorusu Kaynağı are very likely to be those feeding the 5th century channel at Pazarlı and Ergene, and the readily observable remains of intakes at Pazarlı and Pinarca indicate a reasonably consistent approach to design, justifying the imposition of similar conveyance ratios as an appropriate method of estimating inflows in the absence of more detailed information.

Table 1: Maximum capacity of intakes determined from HEC-RAS steady flow analysis

Spring	Pazarlı	Ergene	Danamandıra	Pinarca	Paşa/Binkılıç
Maximum capacity of intake (m^3/s)	0.55	0.15	0.55	0.40	0.55
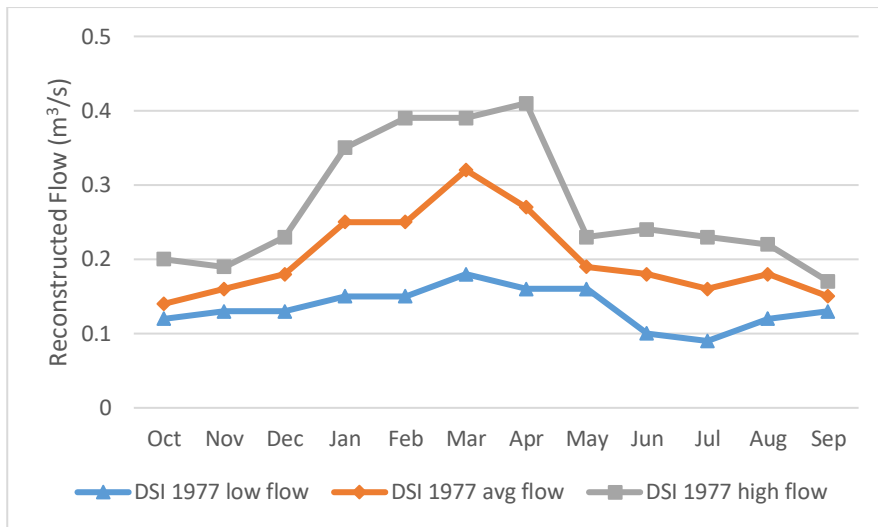
a) Danamandıra
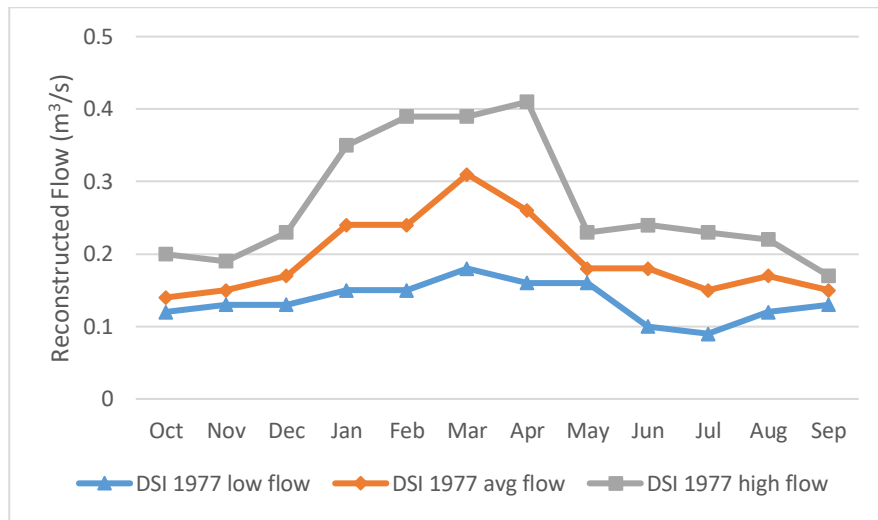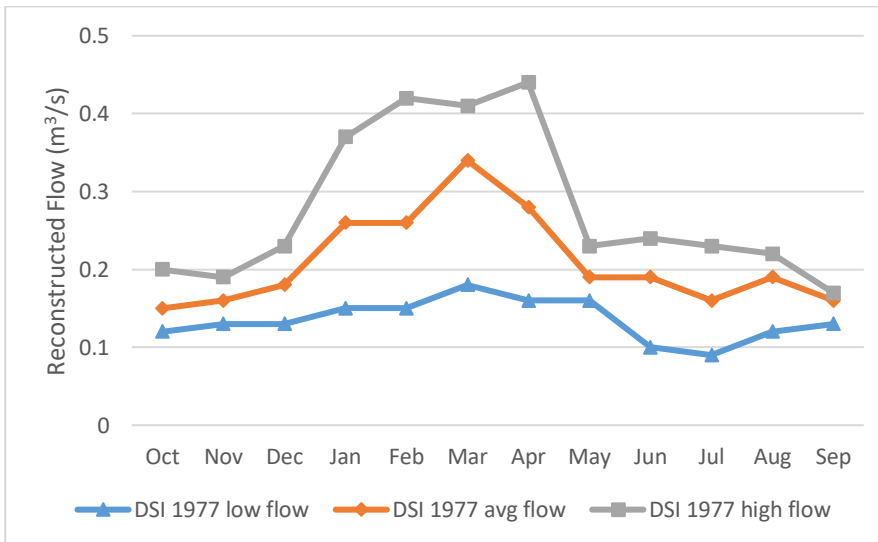
(b) Pinarca

(c) Paşa and Binkılıç

Figure 8: Reconstructed inflow rates for (a) Danamandıra, (b) Pinarca and (c) Paşa and Binkılıç springs, obtained by imposing similar channel conveyance ratios to the Pazarlı – Safalaan and Ergene channels

Hydraulic analysis

Reconstructed inflows for the springs were used as the basis for HEC-RAS simulations of the aqueduct system with the aim of examining aqueduct performance, capacity, and effects such as attenuation of peak flows. The aim of this part of the study was to assess the amount of water delivered to the city and its seasonal variation. Three different possible configurations were examined, these being the 4th century line alone, as envisaged at its original commissioning, the 5th century line imagined as a completely separate system, with a channel parallel, but not connected to the 4th century line from Kalfaköy to the city, and the merged system, assuming that the 5th century construction was an extension to the original, joining with it at Kalfaköy. The systems modelled are illustrated in Figure 9. Modelled reaches were given numbers commencing with IV for 4th century and V for 5th century, as indicated in the figure.

Channel geometry was based on the GIS analysis, with the dimensions of the narrow and wide channels broadly as discussed earlier, modified to precise values where available from field observation and with additional cross-sections interpolated by HEC-RAS every 250 m as recommended to give stable computations. Flow simulations were carried out in the mixed regime to allow for sub- to supercritical flow transition and vice-versa. Full details of the geometry used in the computations are given in (Ruggeri 2018) Appendix D.

For steady flow simulations, the upstream boundary condition at the intakes was set to critical flow, on the basis of the steep nature of the intake channels; for unsteady flow a flow hydrograph provided the upstream boundary conditions. In either case, the downstream boundary condition, representing the point at which the aqueduct system crossed the Theodosian Walls into the city of Constantinople, was set to normal depth, there being no information on which to base an alternative assumption. For unsteady flow modelling, a sensitivity analysis was carried out to determine the effects of computational timestep, and for an hourly flow hydrograph a timestep of 5 minutes was found to give acceptable results.
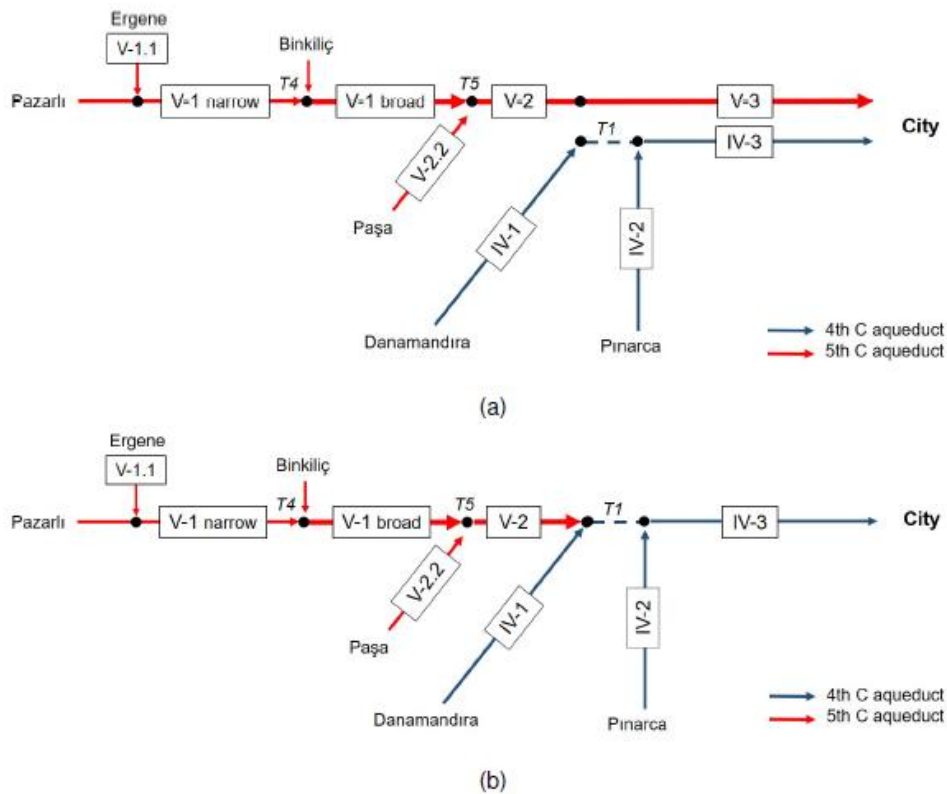
Figure 9: Schematics of the Valens aqueduct simulations; (a) 4th and 5th century lines as separate systems; (b) merged system. The reaches are numbered using IV for the 4th century channels and V for the 5th century (Ruggeri 2018)

Seasonal variation of flow

Steady flow simulations were carried out using the monthly average low, average and high flow scenarios described above; where the aqueduct capacity was exceeded, the flow was capped. In practice this would represent an overflow scenario. No archaeological evidence has been found to indicate the presence of any overflow structures but it would have been perfectly possible for them to be provided.

Considering the 4th century system alone, the maximum capacity of reach IV-3 of 0.7 m^3/s (Figure 9) is reached from February to April for the high flow scenario. In the average flow scenario, the system discharge at the city walls was modelled as 0.28 m³/s in the driest month of October and 0.63 m³/s in the wettest month of March.

Cross-sectional average flow velocities ranged from 0.5 to 0.8 m/s in the main channel, increasing up to 1.5 m/s closer to the intakes where the channel is steeper. This velocity is sufficient to ensure self-cleansing from sediment without undue risk of damage due to scour. Froude numbers are everywhere less than unity, indicating subcritical flow throughout, without the difficulties sometimes associated with flow transitions. Overall the 4th century aqueduct seems to be well designed.

For the 5th century line imagined as continuing all the way to the city walls without merging with the 4th century line, the discharge reaching the city walls was simulated as varying from 0.45 m^3/s to 1.1 m^3/s in the average flow scenario. Velocities were in the range 1.2 to 1.4 m/s, and supercritical flow

was shown only in the Ergene tributary. Here the modelled gradient is steep, but this representation was based on limited information in this area, there being no detailed field observations to feed into the GIS analysis. Model results clearly indicate that, if the inflow estimates above are reasonable, the 1.6 m wide channel in the 5th century system was never mobilized to capacity; at most it was 30 to 40% full. This does bring its ambitiously-sized design into question.

The merged system, Figure 9 b, understandably shows a more significant restriction on aqueduct performance. The already well-utilized IV-3 branch at the downstream end of the 4th century line is now required also to carry the flow from the 5th century line, merging with it at Kalfaköy. This results in significant potential overflow throughout this section, with the aqueduct full for most of the year even at the low flow scenario, and the water being delivered to the city walls being limited to the reach IV-3 capacity of 0.7 m for most of the year.

Plots of the month-by-month flow at the city walls are shown in Figure 10. In Figure 10 a and b, the line represent the average flow scenario with the error bars showing the low and high flow scenarios. In Figure 10 c, for the merged system, only the low flow scenario is plotted as the others use the whole capacity of the aqueduct all year. In the former two simulations, the seasonal variation of flow is apparent.

As mentioned, archaeological investigation has not so far confirmed the arrangement of channels downstream of Kalfaköy after construction of the 5th century line. Separate systems would have delivered much more water (the total being that of Figure 10 a and b combined) but with seasonal variation; a merged system would deliver less water but with significant overflow losses and more constantly over the year.

The population of Constantinople at the time of the Valens aqueduct system's use has been the subject of some speculation. (Jacoby 1961) produced estimates of around 188,000 in the reign of Theodosius II, from AD 402 to 450, rising to 375,000 by the time of Justinian (AD 527-565). Using these as a basis of estimating the per capita use per day, and averaging the month-by-month figures in Figure 10 over the year gives the per capita use for all purposes (including industrial use) as shown in Table 2. The lower figure corresponds to the higher, Justinian-age population. As a reference, a modern design figure for domestic water use is around 200 litres/capita/day. It should be noted that there was also another aqueduct supplying Constantinople, dating from the Hadrianic period, and there were also some wells and rainwater harvesting arrangements providing more local supplies so the figures in the table are not the only water available to the population. Even the lower figures are not unreasonable, though in the drier months there would have been a degree of water stress.
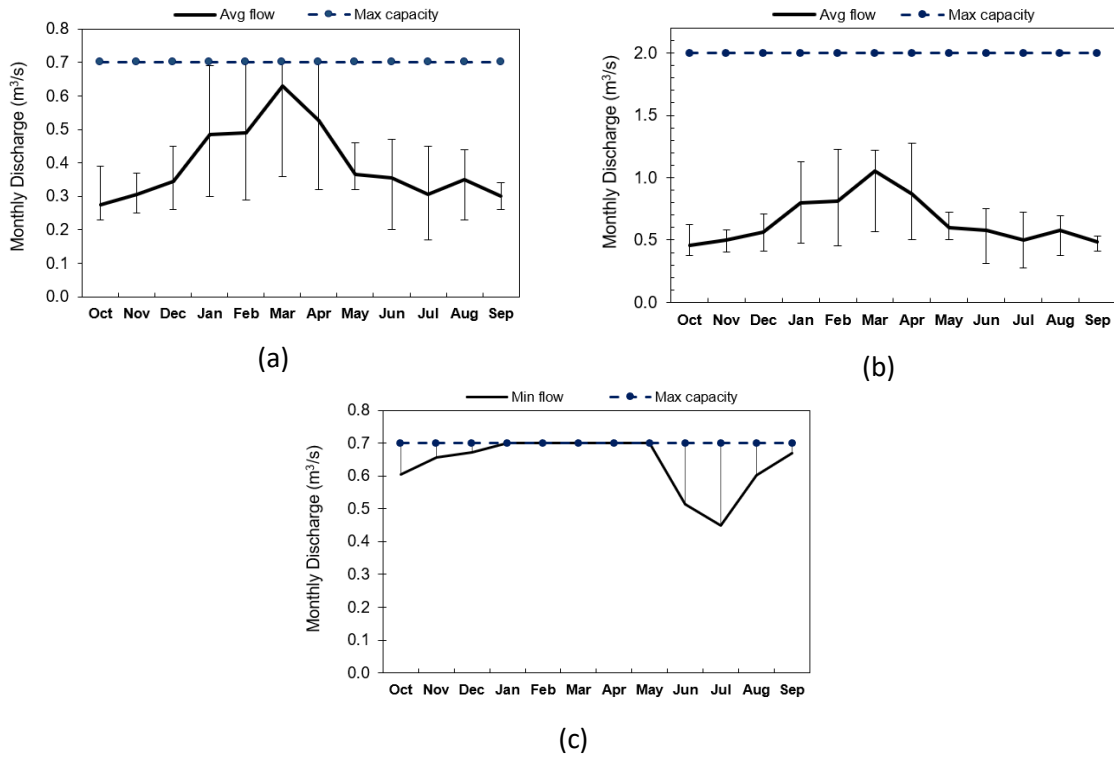
(a)

(b)

(c)

Figure 10: Simulated monthly average flow reaching the city walls for (a) 4th century system, average flow scenario; (b) 5th century system if it continued separately to the city walls, average flow scenario; and (c) merged system, low flow scenario. In each case the maximum capacity of the aqueduct system is shown (Ruggeri 2018)

Table 2: Estimates of per capita flow delivered by the Valens aqueduct for different system configurations, populations and flow scenarios

System configuration	Period (AD)	Population	Average flow over year for different scenarios (m³/s)			Flow per capita per day for different scenarios (litres)		
			Low Flow	Avg Flow	High Flow	Low Flow	Avg Flow	High Flow
4th century line			0.27	0.39	0.51	124	179	234
5th century line	425-450	188000	0.69	1.04	1.36	317	478	625
Merged system			0.64	0.70	0.70	294	322	322
5th century line	527-565	375000	0.69	1.04	1.36	159	240	313
Merged system			0.64	0.70	0.70	147	161	161

Unsteady flow

It is worth considering the possible effects of unsteady flow such as might arise from the rapid response of the springs feeding the aqueduct system to storm events. The maximum and minimum travel time of flow down each leg of the aqueduct was first calculated based on steady flow simulations for the low and high flow scenarios, and is presented in Table 3. The longest travel time for the 4th century system from Danamandıra to Constantinople is almost five days, and that for the 5th century system from Pazarlı to Constantinople was almost seven days, suggesting that considerable attenuation of storm peaks might be possible over these distances. However, the differing travel times for the various reaches suggest that whether or not storm peaks entering the

16

system at the various springs would have coincided further down would be a consequence of many different variables.

Table 3: Travel time for flow derived from steady flow simulations for different reaches of the aqueduct system. The reach numbers are as in Figure 9

4th Century System

Aqueduct Section	Reach	Length (m)	Travel time (hours, min)
Danamandıra to Kalfaköy East	IV-1	66,817	26h 50m - 36h 58m
Pınarca to Kalfaköy East	IV-2	40,787	14h 31m - 19h 59m
Kalfaköy East to Constantinople	IV-3	138,473	60h 17m - 81h 35m
Total for 4th Century System			(days, hours)
Danamandıra to Constantinople	IV-1; IV-3	205,290	3d 14h - 4d 22h
Pınarca to Constantinople	IV-2; IV-3	179,260	3d 02h - 4d 05h

5th Century System

Aqueduct Section	Reach	Length (m)	Travel time (hours, min)
Pazarlı to Ergene Bridge	V-1 narrow	35,766	11h 29m - 17h 00m
Ergene to Binkılıç	V-1 narrow	46,785	17h 42m - 25h 19m
Binkılıç to Ballıgerme South	V-1 broad	35,640	11h 11m - 18h 20m
Ballıgerme South to Kalfaköy West	V-2	54,171	16h 54m - 26h 25m
Kalfaköy West to Constantinople	V-3	138,991	48h 48m - 75h 19m
Tributary channel			
Ergene source to Ergene Bridge	V-1.1	940	1h 23m - 2h 06m
Paşa source to Ballıgerme South	V-2.2	6,981	0h 14m - 0h 20m
Total for 5th Century System			(days, hours)
Pazarlı to Ballıgerme South	V-1	118,191	1d 17h - 2d 12h
Pazarlı to Kalfaköy West	V-1; V-2	172,362	2d 10h - 3d 14h
Pazarlı to Constantinople	V-1; V-2; V-3	311,353	4d 10h - 6d 19h

In order to explore this further, hypothetical six hour-duration storms were simulated using the unsteady flow capabilities of HEC-RAS. The storm hydrographs were simply six-hour blocks of flow corresponding to the previously calculated maximum intake capacity at each spring location, on top of a base flow of 0.1 m³/s. They were introduced simultaneously at the beginning of the situation for each of the five main springs, in this case ordered from upstream to downstream as (1) Pazarlı; (2) Binkılıç; and (3) Paşa on the 5th century line, and (4) Danamandıra; and (5) Pinarca on the 4th century line. Results for the 4th and 5th century system assuming a separate channel all the way to the city are shown in Figure 11 below.

As can be seen, there is some coalescing and attenuation of peaks, though of course had the storm hydrographs commenced at a different start time in the different locations – which is more likely than not in practice, the pattern of coalescence would be different. All are however contained within the various aqueduct channels and would have had minimal effect on the water supply to the city.
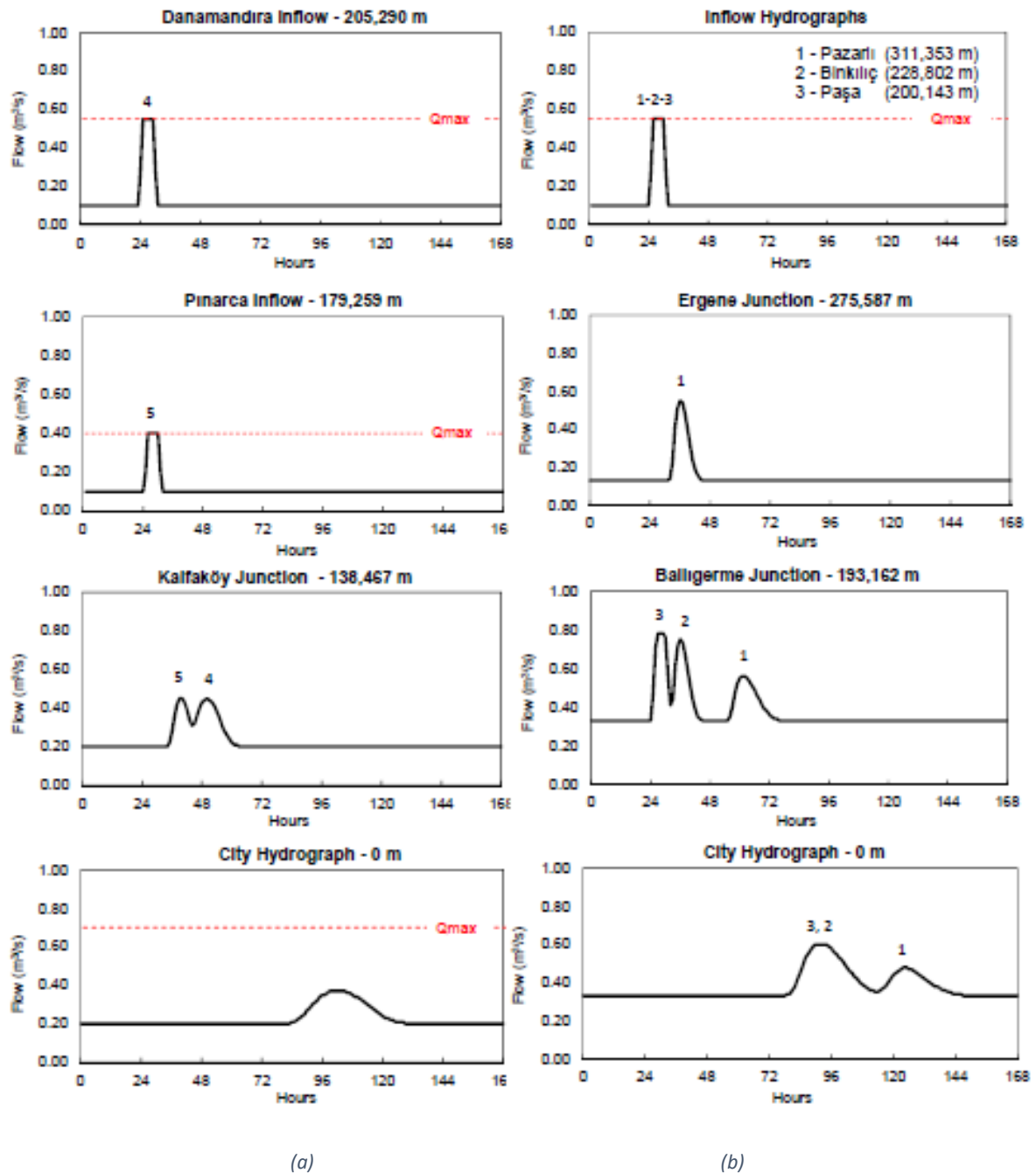
Figure 11: Attenuation of single-peak hydrograph, shown at significant locations (intakes and junctions) from upstream to downstream: (a) 4th century system; (b) 5th century system. Q_{max} indicates the (local) maximum channel capacity where this is not off the scale of the graph (Ruggeri 2018)

Discussion on system configuration

The significant unanswered question is that of the configuration of the Valens aqueduct system downstream of Kalfaköy. Did the 5th century channel continue separately and in parallel to its earlier sister, or did it merge? Related to this question is why the 5th century channel from Safalaan to (at least) Kalfaköy was so large, given that the inflows identified do not appear to utilize anything like its full capacity. There is insufficient archaeology to answer these questions, but engineering analysis may add some insight.

To design a large channel to merge into a narrow channel, as would be the case were the merged system the true arrangement, seems to be poor design, particularly when this leads to overflows of hard-sought and expensively transported water. The only advantage for this is the evening out of water delivery to the city over the year. However, from around AD 421, immediately following the completion of the 5th century aqueduct channel, the city was engaged in constructing cisterns, some of them very large, to store water. These may have been intended for contingencies such as sieges, but even so the investment seems incongruous with the discarding of water from an over-capacity downstream channel in a merged aqueduct system. Another interpretation is that, in the case of separate systems, the seasonal variation shown in Figure 10 a and b became more apparent and measures taken to store water in the wetter parts of the year. Only archaeology will address these questions; in the meantime, based on these engineering design considerations, the author is of the view that the separate, parallel systems is the most likely configuration.

There are many reasons for the upstream channel being wider; for example there may have been, or it may have been hoped there would be additional springs along the route to increase the water supply, though this makes no sense for the case of the merged system. There may also have been some understanding that the wide channel may have had a storage function, perhaps with appropriate controls along its length: perhaps as much as 200,000 m³ of water could have been stored along this length with appropriate engineering. Of course it is also possible that the builder may have been able to make more money from building a larger channel, as has been suggested in the context of the Aqua Anio Novus at Rome (Motta et al. 2017).

Conclusions and Recommendations

A wide ranging hydrological and hydraulic engineering study has been carried out into the Valens aqueduct system serving Constantinople. This aqueduct system is a remarkable achievement of ancient water engineering that is little studied and, outside the centre of modern Istanbul, not being actively conserved and not easily visited.

It was concluded that:

- On the basis of Macrophysical Climate Modelling analysis, modern weather data is a reasonable proxy for climate contemporary with the aqueduct's construction;
- Modern data for the at springs of Pazarlı Ayazma and Çakilli Ergenekorusu Kaynağı is likely to be a good representation of the springs feeding the 5th century channel at Pazarlı and Ergene, and shows a clear seasonal variation with the peak flow being in March and the driest period in October;
- The readily observable remains of intakes at Pazarlı and Pinarca indicate a reasonably consistent approach to design, justifying the imposition of similar conveyance ratios as an appropriate method of estimating inflows at other springs serving different parts of the aqueduct;
- The water delivered to the city depends on the aqueduct configuration in the downstream section, where the 5th century channel may have continued as a separate, parallel line all the way to the city, or may have merged with the 4th century channel around Kalfaköy;
- The flow delivered by the 4th century channel to the city walls ranged from 0.28 m³/s in the driest month of October and 0.63 m³/s in the wettest month of March for an average flow scenario at the springs; for the 5th century line, the flow ranged from 0.45 m³/s to 1.1 m³/s, giving a total range for the two lines continuing in parallel to the city of between 0.73 m³/s and 1.73 m³/s. If the systems merged, the flow delivered to the city was limited by the capacity of the most downstream channel section, this being 0.7 m³/s over most of the year.

- In almost all cases, flow in the aqueduct was subcritical with no difficult flow transitions, and the flow velocities were in the range 0.5 to 1.5 m/s, indicating good design for self-cleansing from sediment without undue risk of scour.
- Estimating the population for Constantinople suggests the aqueduct may have delivered in the range of 124 to 625 litres/capita/day for all uses, averaged over the year; an equivalent modern standard being 200 litres/capita/day. Drier months might have given rise to some water stress; and
- Given that the seasonal variation of flows is apparent in the analysis, that the merged system gave rise to considerable overflows in most flow scenarios, and that shortly after the completion of the 5th century channel, the city embarked upon major investment in large storage facilities, all of which are incongruous with good engineering design, it seems most likely that the 5th century system continued as a separate system all the way to the city; however there is insufficient archaeology to confirm this, or otherwise.

In the light of this, the following recommendations are made:

- Further archaeology should be carried out. In particular, there are at four tunnels on the route of the aqueduct system through Thrace, and remains of these must survive and be identifiable by suitable techniques. Exploration should also be carried out in the area closer to the city in an attempt to confirm or otherwise the existence of separate or merged 4th and 5th century channels;
- Better modern spring flow data for springs close to the aqueduct intake should be sought, for example from modern water facilities or bottling plants, and the hydrological analysis revisited in this light;
- A speleological investigation of the karst at in the region of the aqueduct sources should be carried out if possible to determine in more detail the age, nature and stability of the karst; and
- The aqueduct remains outside Istanbul should be conserved and protected, and made more available to the visitor. This should be done with appropriate interpretation and with sensitivity to the local environment, communities and economy in the region.

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