The Modular Design of Early Byzantine Cisterns and Reservoirs

Charles Anthony Stewart

In the city of Constantia (ancient Salamis), Cyprus, stands a grand Byzantine reservoir known as the Loutron (**fig. 1**). Its final renovation in the early seventh century resulted in a massive rectangular structure supported by 36 piers which formed 52 bays—in terms of volume, it would be the largest vaulted structure ever constructed on the island. It was clearly intended to be a showpiece; built conspicuously above ground to serve as a pendant, facing across the forum towards the famous Temple of Zeus (which had been converted to a church) (**fig. 2**). As such, the Loutron would have resembled the well-known nymphaea of Anatolia. In investigating the structure, wider questions have arisen regarding the development of Byzantine cisterns and reservoirs in comparison to earlier Roman designs.

In Italy and North Africa, the Romans achieved a high level of sophistication in their monumental waterworks. The majority of Roman cisterns were covered with vast continuous barrel-vaults, such as the Piscina Mirabilis (Bacoli) and Malaga (Carthage).[1] By contrast, beginning in the fifth century, the eastern Roman provinces broke from this tradition by incorporating domical or groin-vaults in their cisterns. I suggest in this chapter that these vaulted bays were modular units that facilitated volume calculation during the design process. Recent surveys of Byzantine and Umayyad cisterns and reservoirs in the eastern Mediterranean (Egypt, Turkey, and Palestine), indicate that the driving motivation for this redesign was a need for greater stability—most likely because of seismic activity.

Before I discuss the supporting evidence for this thesis, I should define my terms. *Modular design* is a method in which an architect creates a basic module which can be replicated many times over and, by joining modules together, a larger structure is realized; alternatively, the architect might begin with a design of a complex structure which is then subdivided into congruous smaller units. There are both practical and aesthetic reasons for using modules: simply put, a module can be mass-produced using the same plan and material calculations, and its repetition creates self-similarity which translates into coherent pattern and rhythm. Richard Krautheimer first characterized vaulted bays as "standard units" or modules in Early Byzantine design.[2] In this chapter, the term *cistern* denotes an underground structure that holds and distributes water, while a *reservoir* is a similar building above ground; Byzantine writers made no such distinction. They did adopt the Latin words *cisterna* (κινστάρνα) and *aqueduct* (ὕδωρ ἀγωγόν as a calque of *aquae ductus*) indicating that Roman forms influenced the local Hellenistic building tradition.[3] Such influence was manifested on the island of Cyprus.

I am grateful to the hosts and participants at the *Against Gravity* conference who provided insights, prompting adjustments of my presentation here; moreover, I appreciate the editorial assistance provided by Ms. Virginia Galloway.

[1] Hodge 2002, 276-280; Rossiter et al. 1998. An early exception to barrel vaulting, was the cistern built on Monte Giulio (Ostia Antica) during the 230s, which was constructed with groin-vaulting.
[2] Krautheimer 1986, 242 and 244; Bucher 1972, 37-51.
[3] E.g. Malalas, *Chronographia* XVIII.17; Procopios *Buildings* IV.iv.3; V.ix.36.

Fig. 1. Loutron, Salamis-Constantia (Cyprus). View towards the east (author).

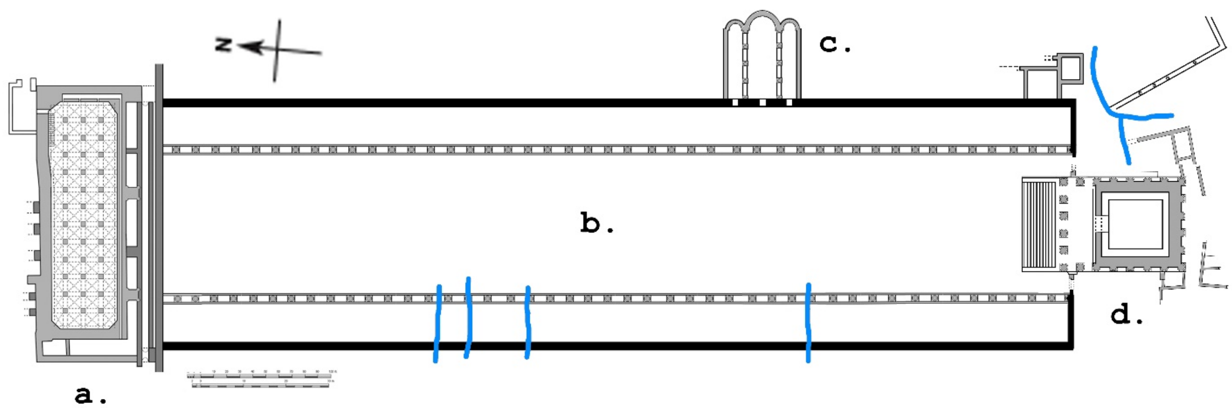

Fig. 2. Forum of Salamis-Constantia (Cyprus): **a.** Loutron; **b.** Open Forum; **c.** church basilica; **d.** Temple of Zeus. Blue lines indicate drains and pipes uncovered by excavations in the 1890s. Redrawn with the author's hypothetical reconstructions, based on the plans of Munro et al. (1891) and Argoud et al. (1975).

The Roman Loutron

In 1888 D.G. Hogarth, a British archaeologist, visited Cyprus and corrected previous theories that assigned the Loutron to the Gothic period, stating that:

> …known to the villagers as the Λουτρόν, appears to me to be not mediaeval, as has been suggested, but of the late Roman or Byzantine work, and to have been a receptacle wherein the water brought in by the aqueduct, whose broken arches still remain… [4]

The designation "Loutron" was first recorded based on the name given to it by modern Cypriots. The name has stuck ever since, though clearly this is a misnomer since λουτρῴν means "bath," and this structure was never used as such; continuity is possible, since "Loutron" could be a corruption of the Byzantine word *elutra* (έλυτρα), denoting "water storage." Of all the monuments of Constantia, the Loutron most impressed visitors throughout history; both local and European explorers remarked on its scale and monumental construction. In 1394, the pilgrim Nicholai Martoni wrote "Here is an ancient cistern, no bigger one is found in the world."[5] In 1750, Alexander Drummond, the English traveler and diplomat, was so awed by its ruins that he decided to measure it and conjectured that it was the substructure of the Temple of Zeus.[6] These early accounts, though incorrect, inspired generations of archaeologists who were drawn to the ancient site.

Luigi and Alexander Palma di Cesnola, in the 1870s, unearthed areas of Constantia, mostly tombs, while searching for artifacts and treasure.[7] More scientific excavations commenced in the 1890s, directed by a British team which included J. A. R. Munro (1864-1944), son of the famous Pre-Raphaelite sculptor Alexander Munro.[8] They partially revealed the Forum's rectangular courtyard; at the southern end they exposed the foundations of the large Temple of Zeus and, to the north, they made the first plans of the Loutron. While research on the Temple of Zeus was recommenced by French archaeologists beginning in 1965, the Loutron has ever since been neglected.[9]

What remains of the Loutron today is an amalgamation of several centuries of building stretching back to the first and second century when funding came directly to the island from the city of Rome.[10] The earliest aqueduct inscriptions credit the Emperor Nero in its construction, implying that a cistern or reservoir would have received water within the ancient city of Salamis at this point. We can presume that the reservoir was damaged by fourth-century earthquakes that prompted a widespread renovation campaign of Salamis by Emperor Constantius II (r. 337 to 361), who renamed it Constantia and made it the

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[4] Hogarth 1889, 61.
[5] Cobham 1908, 25.
[6] Ibid. 301.
[7] Cesnola 1884, xi-7.
[8] J. A. R. Munro's excavation notes of Salamis-Constantia are located at the Ashmolean Museum, Oxford, in the "British Antiquarian and Archaeological Archives."
[9] Argoud et al. 1975, 122.
[10] Nicolaou 1963, 48.

island's capital.[11] Since the Loutron's vaulting and the internal piers were built with different size masonry than the foundations, the British excavators associated the lower level with the Roman period while assuming the vaulting belonged to the Byzantine period.[12]

In the 1989 a German engineer, Mr. A. Baur, visited the site and proposed that the first structure was a typical Roman cistern, barrel-vaulted and underground, evidently ignoring the Byzantine elements of the final reconstruction phase.[13] His publication betrays the fact that he did not consult the original excavation reports, and this led to inaccuracies both in his measurements, plans, and conclusions. For example, he completely ignored the details of the Loutron's south wall facing the forum, which preserved the original buttressing. Fragments of six engaged-columns, with Corinthian capitals, still decorate these supports (**fig.3**). With such a sculpted façade it is hardly plausible that this was a mere cistern, but instead was above ground, as the original excavators noted, since the floor of the Loutron is 1.5 feet (46 cm) *above* the marble pavement of the Forum.[14] Archaeologists were perplexed by the irregularity of the size and spacing of these buttresses:

> That the pier-buttresses are strictly part of the Loutron is perhaps more than doubtful; yet again I could see nothing to suggest that they are not contemporary with it, or were not intended to serve some purpose strictly germane to that of the main building. But the whole problem is one for an architect…[15]

The excavators erred by identifying the Loutron as a *castellum divisorium*; these kinds of buildings, which act as aqueduct terminals for redistribution of water, tend to be designed as practical constructions rather than as visual monuments.[16] While the Loutron did distribute water to other areas around the city, its central location within the Forum indicates that it was also meant to be a spectacle for public viewing. Unfortunately, most of the façade was partly dismantled during the early seventh-century reconstruction phase and was obscured by the mid-seventh-century ramparts; the dismantlement was correctly identified by the British excavators.[17]

Based on the visible remains, it is possible to make a hypothetical reconstruction of the Loutron as a Late Roman barrel-vaulted structure (**fig. 4**).[18] Most likely, the façade served as a *nymphaeum*, that is, a public water fountain which would have been easily fed by the reservoir behind it. Nymphaea are quite common in the Roman province of Asia Minor, as at Aspendos (**fig. 5**) and Sagalassos; these have undulating wall surfaces partly shaded by porches and partly open, resembling backdrops in theaters. The Loutron at Salamis was like the Nymphaeum at Miletos—the only other example of a Nymphaeum

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[11] John Malalas, *Chronographia*, XII, 48; Stewart 2014b, 1-2.
[12] Munro et al. 1891, 89-91.
[13] Baur 1989, 203-18.
[14] Munro et al. 1891, 81-83.
[15] Ibid. 89.
[16] Ibid. 89; Hodge 2002: 2-3.
[17] Munro et al. 1891, 89.
[18] There is a comparable design of a barrel-vaulted cistern at Silifke (Turkey), known as Tekir ambarı, which seems to be belong to the Byzantine period. Silifke is 81 miles (130 km) north of Salamis-Constantia.

Fig. 3. Loutron, Salamis-Constantia (Cyprus). Remains of an engaged column, adorning a square buttress (author).

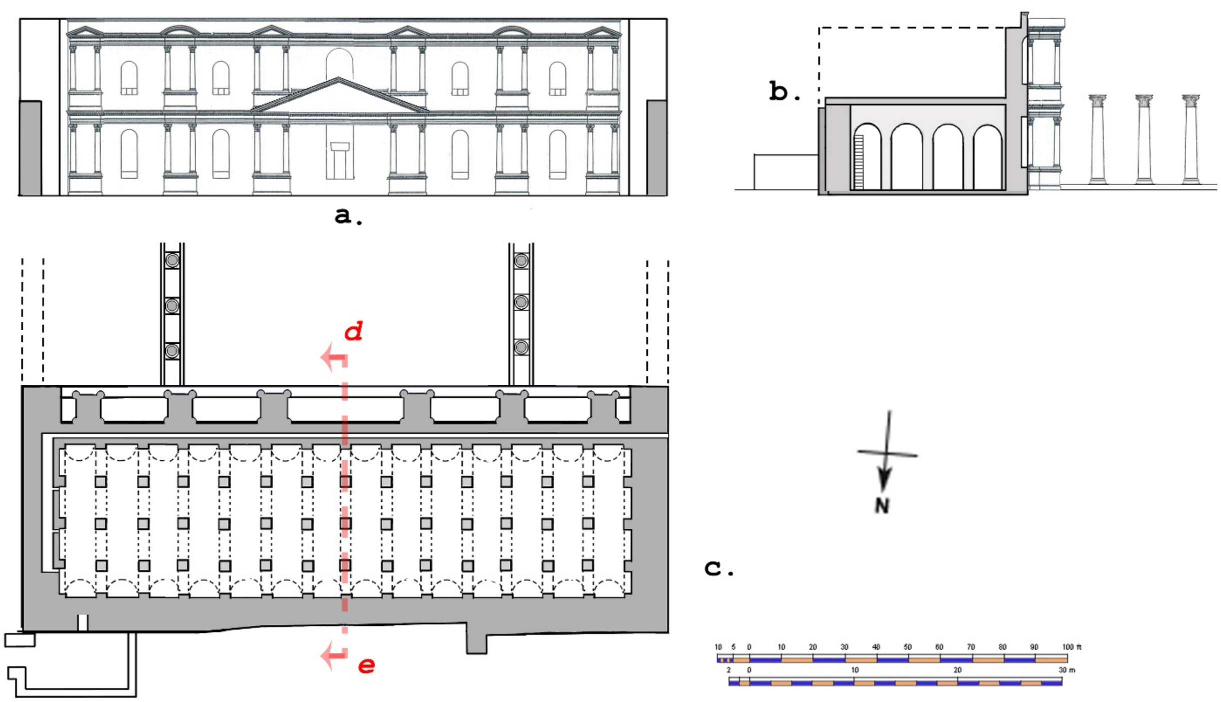

Fig. 4. Loutron, Salamis-Constantia (Cyprus). Hypothetical reconstruction of the Late Roman phase: **a.** Nymphaeum façade as seen from the Forum; **b.** section designated *d-e* on ground plan; **c.** ground plan (author).

Fig. 5. Nymphaeum, Aspendos (Turkey). Remains of the Façade (author).

that was attached directly to a reservoir (thus directly fed by an aqueduct).[19] Surviving remains of the Loutron's façade indicate that it was not as lavishly decorated with marble revetment or reliefs like those in Anatolia; however, this could be simply a result of historical accident, since bits and pieces of marble do litter the ground and a well-crafted marble ram's head was found within the Loutron, which might be a remnant of the original façade.[20]

Most nymphaea in Anatolia are dated to the second century and associated with the reign of Trajan, so it is plausible that the Loutron's façade was first constructed in the same period, when Salamis was restored after the local Jewish revolt of 117.[21] Around the same time, the Sette Sale cistern in Rome was constructed for the supply of the Baths of Trajan; in order to strengthen this cistern's walls against the water pressure inside, a series of external niches were constructed around the complex.[22] These served as external buttresses and were eventually buried from public view. Also in the second century, a series of external niches were added to the northeastern side of the Piscina Mirabilis (Bacoli, Italy) that served as buttressing while allowing light and air into the complex. Apparently external buttressing was a practical solution to strengthen cisterns while not challenging classical aesthetics since they were buried and invisible to the public.

Inherent to the Loutron's design were the external buttresses of the façade; unlike the Italian examples, however, they were intended to be above ground and conspicuous for public viewing. This characteristic is an important design difference between the Loutron

[19] For general discussion see Ward-Perkins 1992, 299; for Aspendos, see Hörmann 1929, 263-274; for Miletos, see Wiegand 1919,
[20] Myres and Ohnefalsch-Richter 1899, 114.
[21] Dio Cassius, *Historia Romana* 68.32.
[22] Staccioli 2005, 75-80 and 186-190.

and the Anatolian nymphaea, and implies a later date. What I mean is that in the Anatolian examples actual porches decorated their façade, while in the Loutron buttresses were disguised as porches. As I have argued elsewhere, the use of external buttressing as a standard visual device arises no earlier than the late third century.[23] That is why my working hypothesis presumes that the remnants of façade—as it currently exists—date to the time of Constantius II, when Salamis was renamed Constantia. Only with a proper excavation of the site can this dating be clarified; nevertheless, in the wider history of architecture we can trace the spread of the concept of external buttressed cisterns in the Trajanic period to later Byzantine examples, like the open-air Fildami Reservoir and the Unkapani Cistern in Constantinople.[24] Within this line of development, the Loutron's facade fits somewhere between the reigns of Trajan and Justinian.

As a nymphaeum, the Loutron was integral to the overall design of the Forum (**fig.2**). The Temple of Zeus faced the Loutron and was built to resemble a first-century Roman-type temple with these characteristics: a tall podium, deep porch, and engaged columns (**fig.6**). Regrettably, not much of the temple's superstructure survives today since, throughout history, the fabric was mined for building material. British archaeologists in 1891 discovered Byzantine mosaics in the north eastern corner of its cella; as they dug below the mosaics, their work was hindered by rising ground water, which is surprising given the aridity of the island during the summer. Apparently the temple was built on a natural spring, enshrined by an exterior niche on the eastern wall which gave access to this water source. The fountain would be maintained into the Early Byzantine period, when the Temple of Zeus was converted into a church (**fig. 7**).

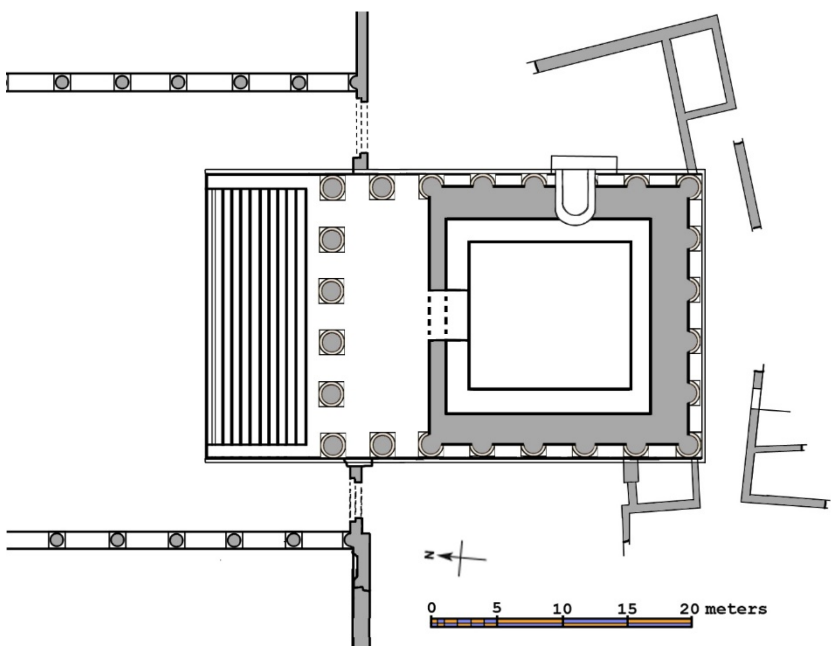

Fig. 6. Temple of Zeus, Salamis-Constantia (Cyprus). Hypothetical reconstruction of the cella ground plan. Note the fountain niche on the eastern wall. Redrawn based on the plans of Munro et al. (1891) and Argoud et al. (1975).

[23] Stewart 2014b, 6-9.
[24] Crow et al. 2008, 132-141; Ergil 1974, 42-7.

Fig. 7. Temple of Zeus, Salamis-Constantia (Cyprus). Fountain in the eastern wall, looking north. Note the difference between the Roman ashlar masonry on the left with the Byzantine brickwork on the right (author).

Architects and engineers designed the Salamis-Constantia Forum to showcase particularly Roman forms and engineering ability while also celebrating natural sources of water. The 30-mile long (48 km) aqueduct was a major imperial investment on Cyprus—the first of its kind on the island—which filled the Loutron that, in turn, powered the fountains and baths around the city. Likewise, the Roman-style Temple of Zeus enshrined an ancient spring, which also should be associated with another natural water source 600 yards (558 m) away, the Pedieos River—the longest river in Cyprus. The architects who designed the Forum were highlighting the artificial water source, the Loutron, and natural water sources enshrined at the Temple of Zeus. In other words, the Forum celebrated the artificial and natural sources of water on which this city depended, as well as the government and supernatural powers that made this possible. This signification would have been maintained in the Byzantine period but, of course, reinterpreted in a Christian sense.

The Byzantine Loutron

The Loutron was renovated sometime in the Early Byzantine period. Most likely this took place during the reign of the Emperor Heraclius, coinciding with the reconstruction of the adjacent aqueduct, which is documented by several inscriptions.[25] The final phase of

[25] Stewart 2012, 1-19; Stewart 2014b, 11-15.

the rebuilding focused on erecting piers and covering the space with groin vaults (**fig. 8**). At that time, a new barrel-vaulted passage was constructed to redirect water from the aqueduct to the basin, effectively obstructing the façade and thus destroying the classical nymphaeum (**fig. 9**). The passage led to new vaulted sections against the south wall, designed to enhance the water filtration process as settlement chambers (**fig. 10**).

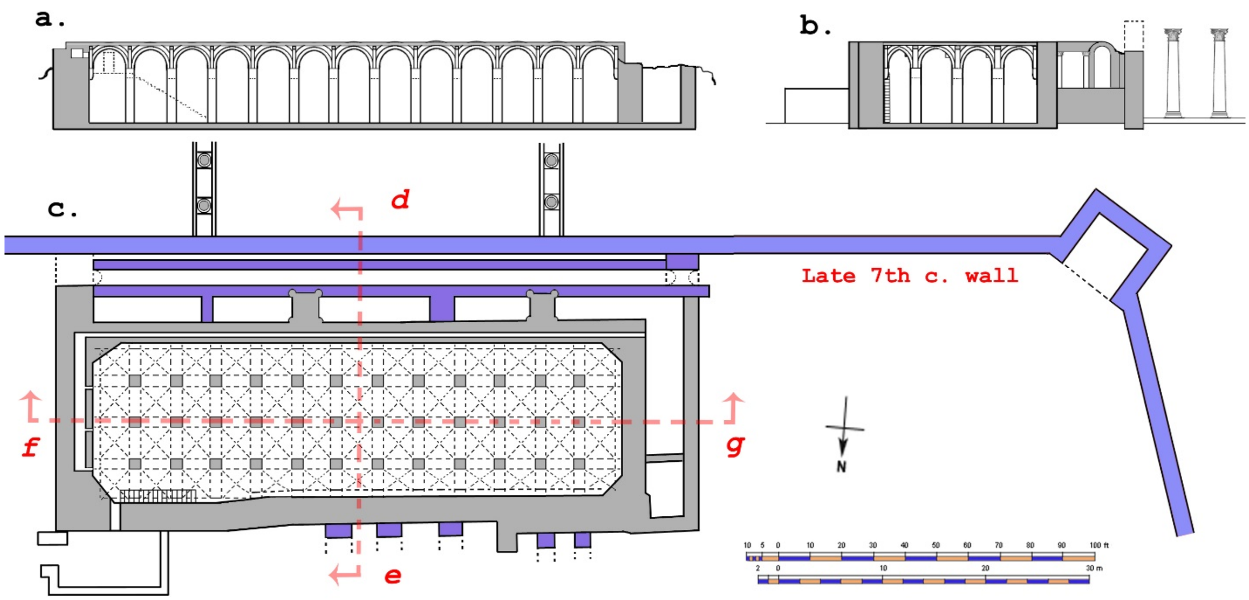

Fig. 8. Loutron, Salamis-Constantia (Cyprus). Byzantine renovation phase: **a.** elevation section *f-g*; **b.** elevation section *d-e*; **c.** ground plan, redrawn based on the plan of Munro et al. (1891) with modifications (author). Purple: early 7th renovations; Blue: late 7th c. wall.

The form of vaulting is evident from the surviving corbels and arches located on all four of its walls (**fig. 11**). These corbels carried transverse arches that spanned inward to the thirty-six internal piers, forming fifty-two bays in a grid pattern, which has, admittedly, irregular dimensions (**Figs. 12 and 13**). Each bay was covered with either groin vaults or domical vaults.[26] Clearly this design is similar to the groin-vaulted Basilica Cistern in Constantinople (built around 532) (**Fig. 14**), but is also somewhat different because of the Loutron's use of piers instead of columns and irregular ashlars rather than standard-size bricks. Also unlike the Basilica Cistern, the Loutron is above ground, needing massive walls about 4.5 m in width with an additional series of large pier-buttresses (or perhaps flying buttresses) at the north wall that further strengthened the new vaulting system.

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[26] In some Roman and Byzantine cisterns in the east [e.g. Qanawat (Syria), Mampsis (Israel), and Humeima (Jordan)] arches and piers support flat slabs of stone rather than vaulting. It is not possible that the Loutron was covered this way since this method requires a continuous internal ledge or walls to support the ends of the stone slabs. There is no evidence that the Loutron's pier system supported a continuous ledge; moreover, no large stone slabs have found in this location, while the interior is filled with small ashlars which we can presume are the remains of the vaulting.

Fig. 9. Loutron, Salamis-Constantia (Cyprus). Byzantine renovation phase: barrel-vaulted passage between earlier façade (right) and later wall (left) (author).

Fig. 10. Loutron, Salamis-Constantia (Cyprus). Byzantine renovation phase: settlement chamber between reservoir and barrel-vaulted passage (author).

Fig. 11. Loutron, Salamis-Constantia (Cyprus). Byzantine renovation phase: Corbels and arches forming the vaults (author).

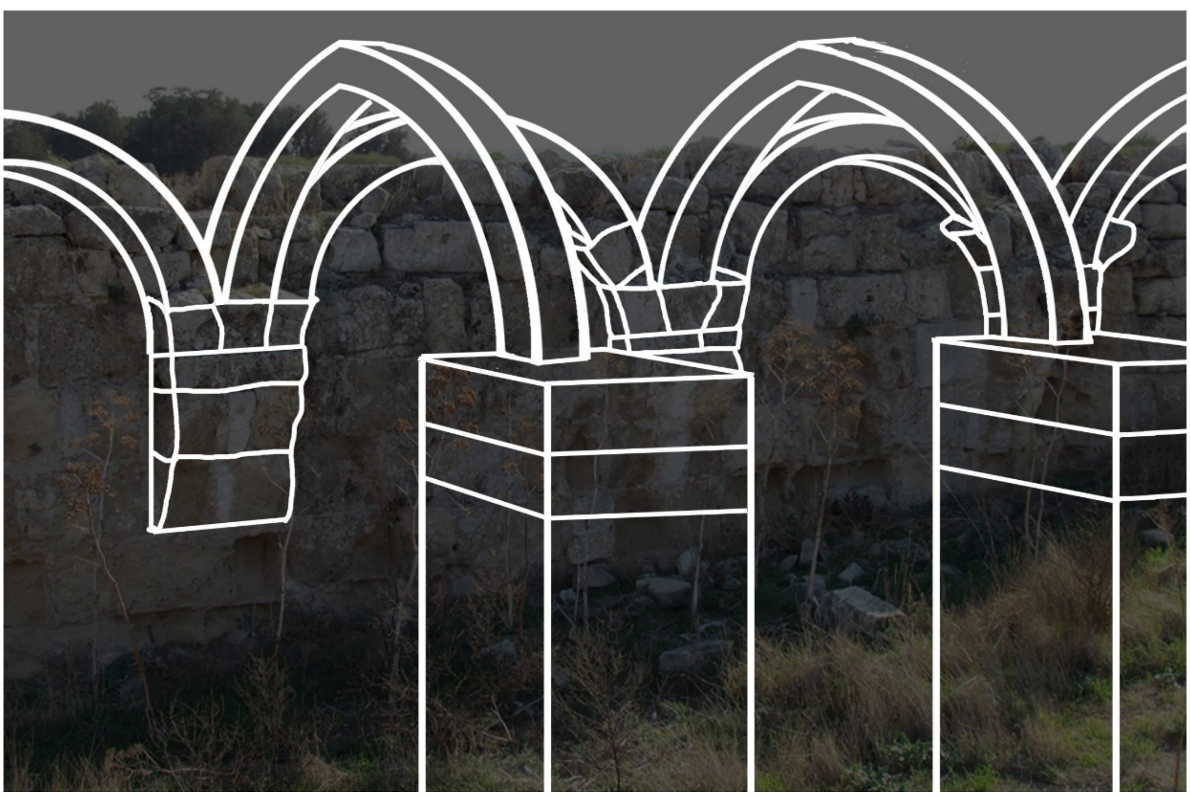

Fig. 12. Loutron, Salamis-Constantia (Cyprus). Byzantine renovation phase: Conceptual overlay (of **Fig. 11**.) illustrating how transverse arches spanned from wall to internal piers (author).

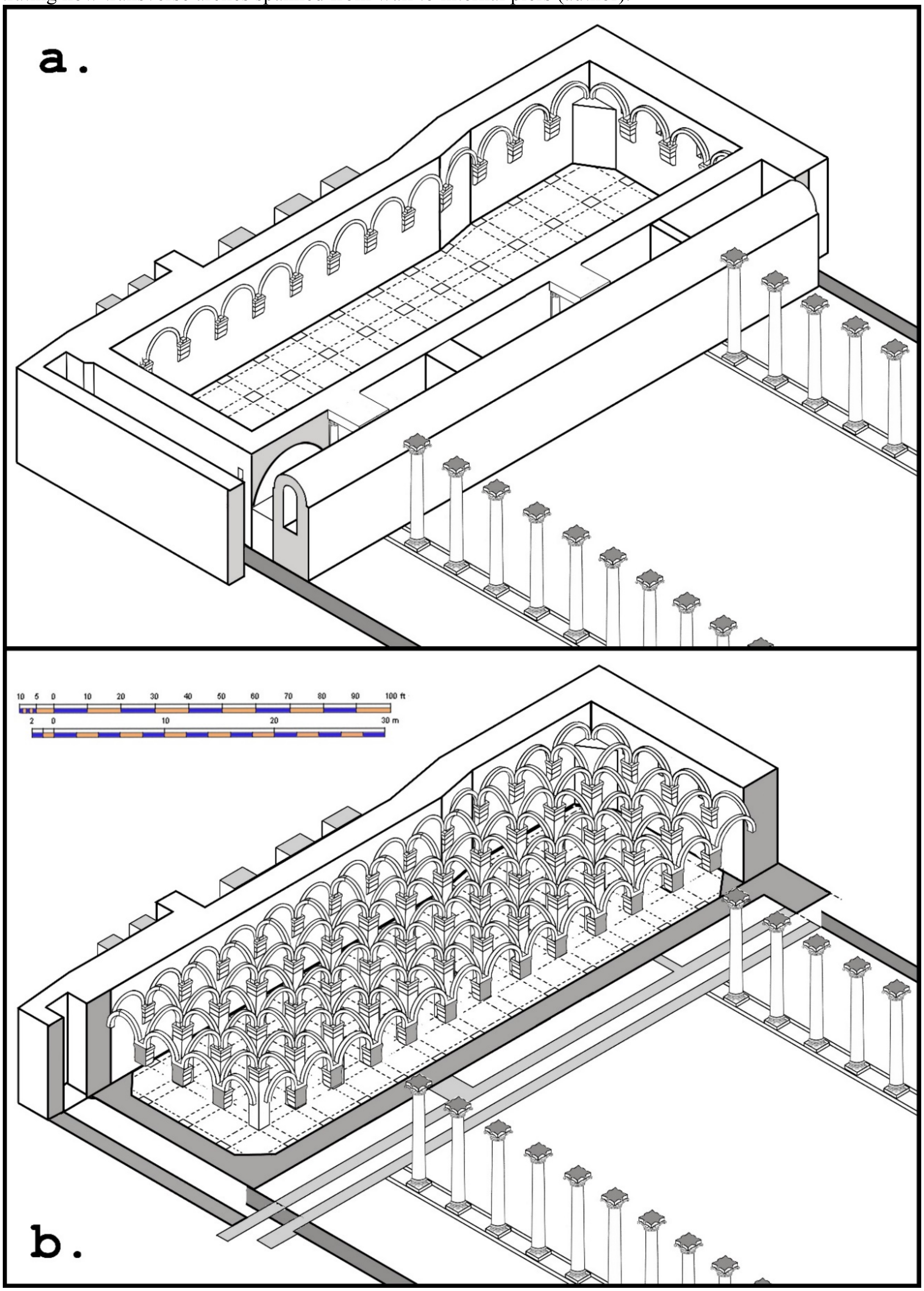

Fig. 13. Loutron, Salamis-Constantia (Cyprus). Isometric cutaway of the Byzantine renovation phase: **a.** corbels and pier layout; **b.** layout of vault's transverse arches (author).

Fig. 14. Basilica Cistern ((Yerebatan Sarayı), Constantinople, ca.532. Vaults (author).

The question remains: What prompted Heraclius to rebuild the aqueducts and the Loutron? Based on the inscriptions at Chytroi (Cyprus)—where the water source of the Constantia aqueduct originated—it seems that Emperor Phocas had already begun the construction of the aqueduct sometime in the first decade of the seventh century.[27] Earlier, in the year 580, there was a major earthquake centered somewhere along the southernmost coast of Pamphylia. Excavations in the city of Anemorion (Anemur, Turkey), just 65 miles from Chytroi, has established that aqueducts in that city were damaged, precipitating its rapid decline.[28] Perhaps this same earthquake caused the waterworks of Constantia to need reconstruction.

The Loutron provides a good case study of the ways a classical Roman structure was remodeled using Byzantine design concepts and techniques. In redrafting the plans and conceptualizing how the building functioned (both practically and aesthetically), I noticed that spacing of the piers and the measurements of each bay corresponded with the elevation; that is, the height is twice the length of the average side of the bay (measured

[27] Stewart 2014b, 25-26, notes 23 and 25.
[28] Russell 2007, 222.

from the middle of the piers) (**fig. 15a**). As such, each bay contained approximately two cubed modules (**fig. 15b**). Four bays combined form a larger cubed unit—that is, the module squared; altogether there were 12 of these larger groups (**fig. 15c**). One row or four additional bays were added, which held the volume of two half-cubes, that is, one large cube. In other words, the internal volume of the Loutron consisted of 13 large cubes, consisting of a total of 104 smaller cubed modules (**fig. 15d**). Because this space was intended to be filled with water, the abstract conceptualization of cubic (three-dimensional) space seems to be inherent in its redesign.

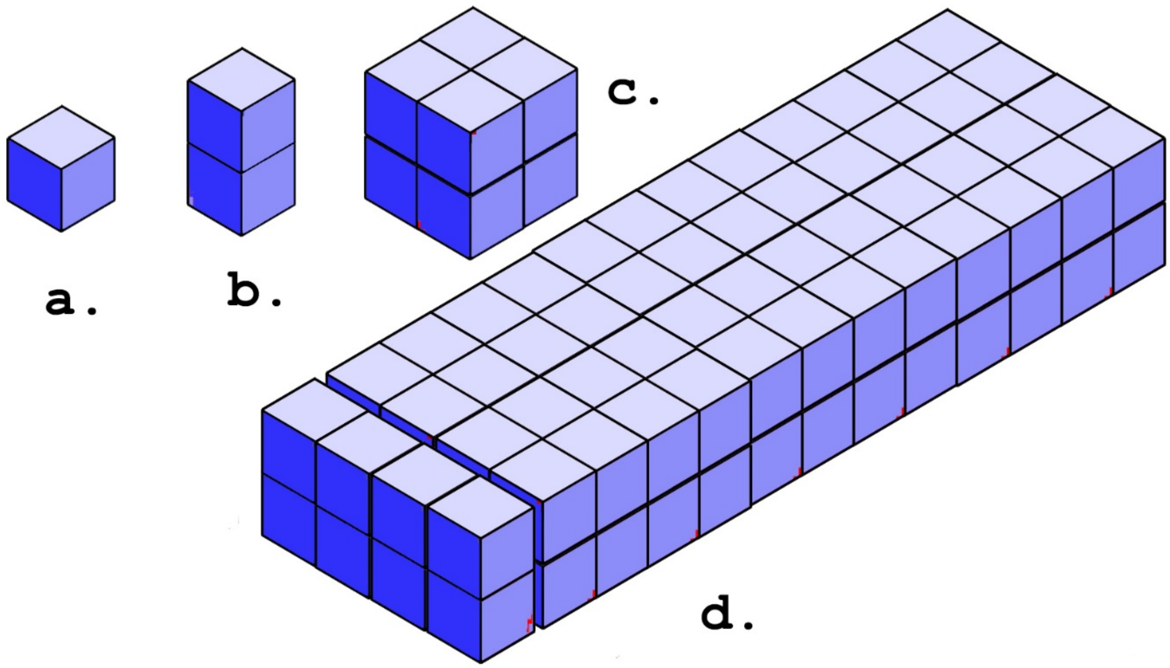

Fig. 15. Conceptual Diagram of the Loutron's volume based on its modular design: **a.** module; **b.** bay; **c.** large cube = four bays (8 modules); **d.** total volume consisted of 12 large cubes, i.e. 96 modules [and an additional 8 modules or 2 half-cubes (i.e. one large cube)] (author).

Volume is calculated by multiplying three dimensions. Water could fill the Loutron up to the level of the vault springing, since this is where water channels from the aqueduct are located. Volume can be calculate in the traditional way: length (52.5 m) multiplied by width (15.5 m) multiplied by height (5.2 m), which equals 4,231.5 m^3. With knowledge of its modular design, we can calculate its volume in another fashion: 1 bay's volume [79 m^3 (consisting of 1 module, 52.7 m^3, plus the space up to the springing, which is half a module, 26.3 m^3) multiplied by 52 bays, totaling 4,108 m^3. It is possible that, as they redesigned its vaulting, the Byzantine architects envisioned the Loutron's space as a set of 104 square modules instead of one large rectangular cuboid as most modern researchers view it.

While the Loutron has no precise right angles and its pier spacing is irregular, the dimensions still seem to correlate better with Byzantine rather than Roman measurement units. We can compare the Roman Foot (*pes monetalis*, RF), which varied between 0.294 m to 0.297 m, with the Byzantine Foot (ποῦς, BF), varying between 0.3123 m and 0.315 m.[29] The renovators, in reusing the foundations of the earlier Roman structure, simply divided the Loutron's interior based on the Byzantine system; thus, the dimensions were approximately 168 BF by 50 BF, and each bay's side could be conceptualized—in round numbers—to about 12 BF from the middle of each pier (that is, 3.75 m divided by 0.3123 m), and so each module could be estimated as holding 1,728 BF^3, giving the entire structure the volume of 134,784 BF^3. It is possible that the architects used these modules in calculating the dimensions of the space they were given and that this governed the size of each bay and, thus, the size of the vault's transverse arches. It is unlikely that the modules mattered after construction was complete, since volume is easily calculated by measuring the ever-changing water level and then multiplying that by the fixed dimensions of the interior.

Modular design allowed Byzantine architects to visualize and estimate volume of large structures. For ancient civilizations, the calculation of volume was important for the building of granaries and, as a consequence, estimating the yearly food supply. Byzantine writers often paired granaries with cisterns.[30] The earliest surviving treatises regarding the calculation of granary volumes are the *Moscow Mathematical Papyrus* (ca. 1700 BC) and the *Rhind Mathematical Papyrus* (1650 BC); ancient practical formulas like these would have been passed to the Hellenistic rulers of Egypt and on to the Romans.[31] The same principles were used to calculate water volume, especially in the Roman period, when the costly water of aqueducts had to be deposited in structures suitable to receive and store it.[32] Size of cisterns and reservoirs varied based both on the amount of water carried by the particular aqueduct and local population use; such computation and water economics were quite sophisticated and required highly-trained engineers.[33] While it is possible that such highly-educated individuals resided in Cyprus, it seems unlikely, since the Loutron is unique for the island.

Constantinopolitan Designs

There is little doubt that the design, as well as the funding for the reconstruction of the Loutron, came from Constantinople. The imperial capital has the largest reservoirs and cisterns of the ancient and medieval world, and it seems to have had the most in terms of quantity. While the study of the city's waterworks has garnered attention of scholars since the inception of Byzantine studies, we are only beginning to understand the full extent of its engineering principles, scale, and the historical development.[34] Imperial engineers and architects, particularly those who specialized in water-related structures, must have been trained within Constantinople, since the lack of fresh water was one of its key strategic

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[29] Regarding Roman measurement, see Jones (2000, 71-74), and for Byzantine measurement, see Schilbach (1991, 1708) and the discussion by Ousterhout (2008, 75-76).
[30] E.g. *Chronicon Paschale* (Whiby and Whitby 1989, 127); Malalas, *Chronicle* 18.71.
[31] Clagett 1999, 13-14, 80-81.
[32] Frontinus' *De Aquis* and *Strategemata* are concerned about calculating the daily water flow through gauges, which is much more complex than a simple architectural volume (ed. Bennett 1925, xvi-xvii).
[33] Ibid.; see also, Hodge 2002, 171-184.
[34] Andreossy 1828, 440-445; Forchheimer and Strzygowski 1893; Müller-Wiener 1977, 271-285; Mango 1995, 9-18; Rautman 2006, 72–75; and Crow et al. 2008.

weaknesses; therefore, of all the types of architecture, we can presume that Constantinople had the most innovative waterworks within the Empire's domain.

When we compare the design of the Loutron with the cisterns of Constantinople, we see three main similarities. First, in the interior, where we would expect to find 90-degree angles where the walls join, we instead encounter chamfered corners; this additional masonry strengthens the juncture where internal water pressure would be concentrated [e.g. as at the Basilica Cistern (Yerebatan Sarayı) and Philoxenos Cistern (Binbirdirek Sarayı)] (**figs. 16 and 17**). Second, the use of square grids is apparent in nearly all the monumental cisterns and reservoirs in Constantinople, forming a network of bays grouped into square or rectangular plans.[35] The Basilica Cistern, for example, consists of 377 bays supported by 336 columns; as such, the plan can be conceptualized as two perfect squares consisting of 169 modules and three additional rows with 39 modules. These large squares are implied by the later rubble walls that reach towards the central bay of the northernmost square (**fig. 16**).[36] Third, almost all Constantinopolitan monumental cisterns use groin-vaulting (or domical vaulting) supported by columns (or piers) indicating a general "Byzantine style" of cistern construction which was different from the earlier "Roman style" that preferred barrel-vaults.

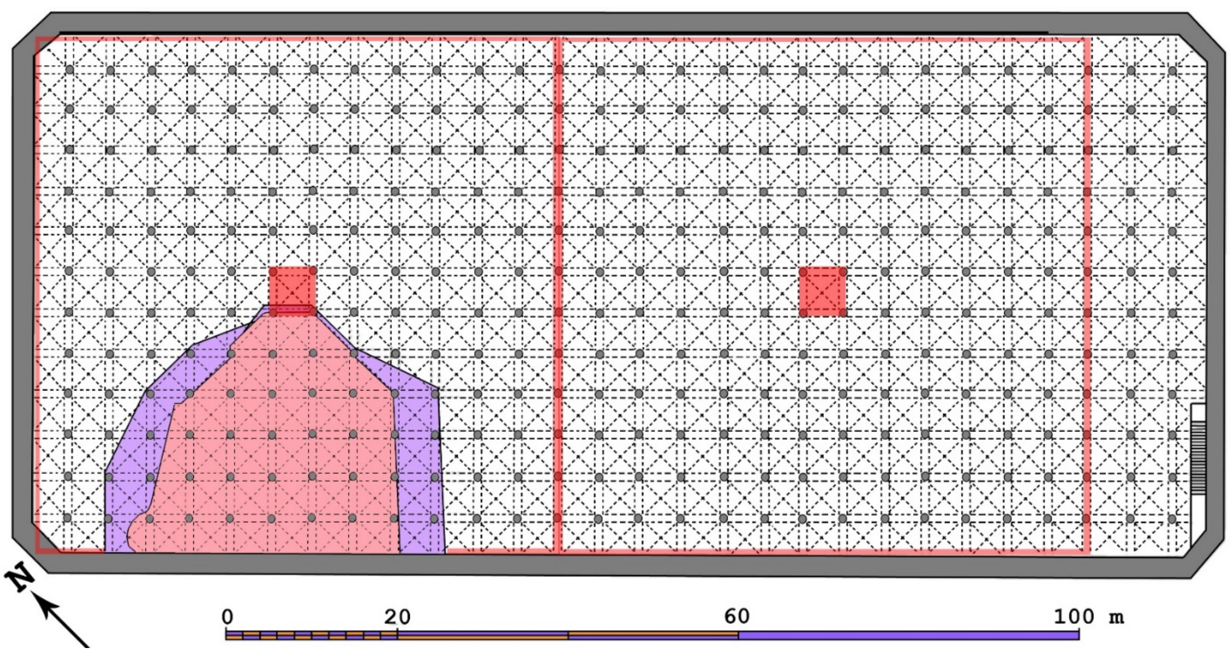

Fig. 16. Basilica Cistern (Yerebatan Sarayı), Constantinople, ca. 532. Ground plan. Red squares indicates central modules; red outlines mark larger square units; pink and violet areas are later walled-off areas (redrawn based on the plans of Akgül 1980, 48, and Müller-Wiener 1977, 285) (author).

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[35] For example, see the comparative diagram in Crow et al. 2008, 215-216.

[36] The internal rubble walls necessarily approached the centermost bay of the large square; by bolstering the innermost module, the entire structure was reinforced. Today these walls obscure a section consisting of 40 columns. Since they are rubble masonry, they are not part of the original brick design, and appear to be earlier than Muhammad Agha of Kayseri's renovations that date to 1723 (Müller-Wiener 1977, 285 caption 323).

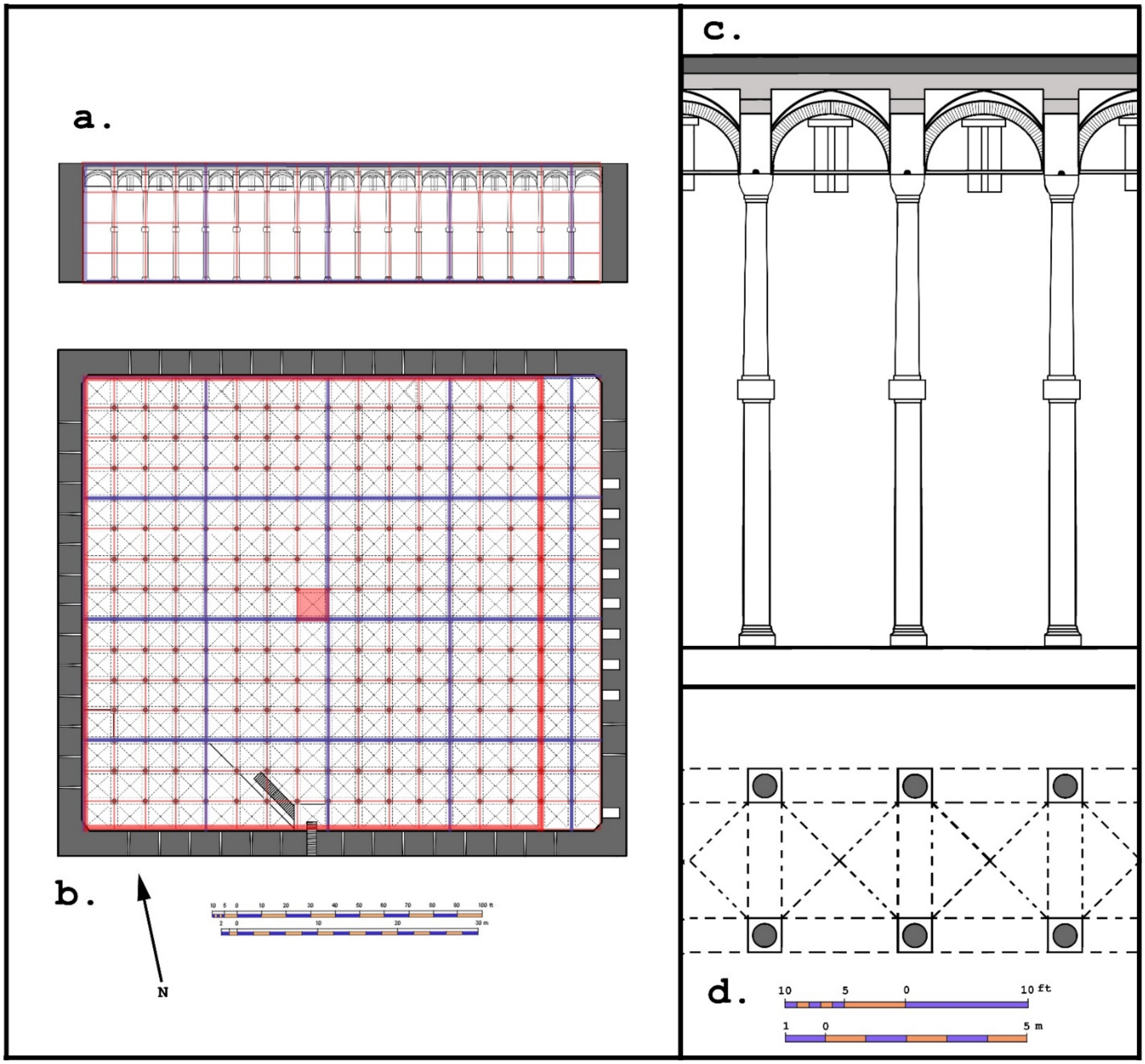

Fig. 17. Philoxenos (Binbirdirek Sarayı), Constantinople, 6th century: **a.** elevation; **b.** ground plan; **c.** elevation detail; **d**. ground plan detail. Small red lines = square grid; large red outline demarcates the large square; solid red area = central module facing entrance; blue lines = cube units (redrawn by author based on the plans of Andreossy 1828 and Forchheimer and Strzygowski 1893).

The Philoxenos Cistern (Binbirdirek Sarayı) presents a good case study in Byzantine modular design. It consists of a network of 255 bays supported by 224 columns; as such, the plan can be conceived as a larger perfect square consisting of 225 bays and two additional rows with 30 more bays. The larger square is implied by the original entrance which faces the central bay (**fig. 17b** and **18d**). The height was proportional to the square plan of the bays; that is, the height of each bay is four bays tall or, in other words, each bay consists of four cubic modules (**fig. 18b**), When 16 bays are grouped together, they form a larger cube (**fig. 18c**); altogether there were 12 of these larger groups (**fig. 17b**). When the remaining modules are combined, another three larger cube units could be formed; a fourth cube is almost possible, but lacks one bay (four modules) to complete it. Simply put, the internal volume of the Philoxenos Cistern is one bay shy of being conceptualized as 16 large cubes consisting of 64 modules each; therefore, the total number of modules equals 1020 (**fig. 18d**). Because this space was intended to be filled with water, the abstract conceptualization of cubic space was inherent in the Philoxenos Cistern's design and, as we seen, similar to the basic design of the Loutron in Cyprus.

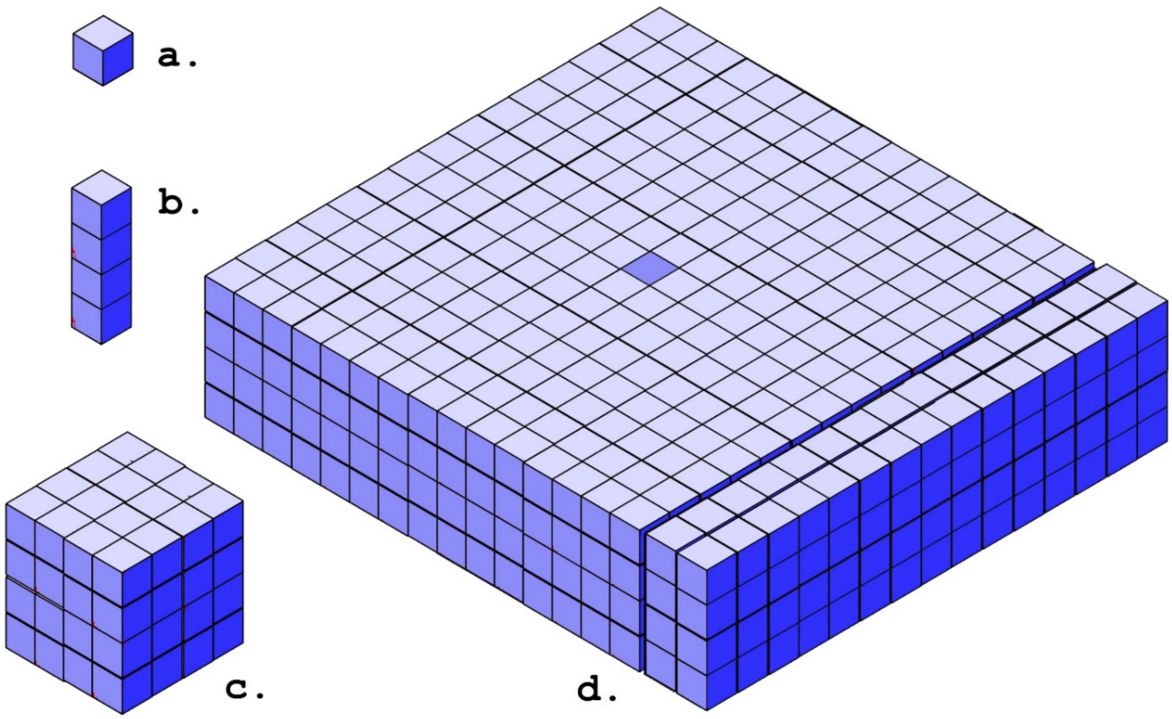

Fig. 18. Conceptual Diagram of the Philoxenos Cistern's volume, Constantinople, 6th century: **a.** module; **b.** bay; **c.** large cube; **d.** total volume (small dark blue square indicates central bay) (author).

Since architectural manuals and plans do not survive, scholars have to rely on archaeological reconstructions and formal analyses to understand Byzantine methods and planning. Because architects were able to construct complex colossal monuments, it was critical that they plan accordingly before construction commenced. By envisioning their reservoirs and cisterns as modular units, Byzantine architects could calculate volume during the design process. Each bay formed a distinct modular unit; by adding additional bays, the architect could determine, in an incremental fashion, how much volume increased when the dimensions of the building were lengthened. No doubt architects were commissioned to design structures to hold a particular quota based on local population demands or the fixed output of the aqueducts; moreover, since space in Constantinople was circumscribed, calculating a cistern's necessary depth and height was essential to make sure that the required volume was realized. Cumulative calculation—from module to bay and then to large cube—allowed the architect to brainstorm all the possible configurations that the limited space provided.

There were other key advantages to modular design. First, monumental cisterns in Constantinople appear cavernous and complex; reducing such spaces to a series of cubes allowed architects to manage their preliminary plans in the simplest of terms. This kind of abstraction through visual forms is called today "combinatory thinking" and is sometimes illustrated in Byzantine copies of earlier classical texts on architectural measurement. [37] Second, the estimation of materials, cost, and time was much easier to determine using modular units; architects only needed to make calculations for one bay and then multiply that number accordingly. Third, it was easier for architects to explain the *construction* of one modular bay to the master-builders, who then provided *instruction* to their teams of masons. Fourth, different teams could easily join their sections together, since they understood other teams' modules; presumably, the workmen became more adept after each bay was completed, because with repetition comes efficiency. These four advantages could have been realized through many centuries of "trial and error" in building practices; however, there is no reason to suppose that such practical knowledge could not have been guided by experimental engineering and theoretical design, since those who ruled the Early Byzantine Empire and their imperial architects were provided with a classical education.[38]

It is hard to separate theory and practice in Early Byzantine architecture when we understand the wider context. For example, the Basilica Cistern literally lay underneath the University of Constantinople (Πανδιδακτήριον) which was founded in 425 AD and functioned throughout the Byzantine period.[39] While its students focused on rhetoric and law, they would have encountered mathematical theory in their philosophical studies. Certainly the university held the repository of classical mathematical texts from which architecture students learned general engineering and numerical principles.[40] In both elementary and higher education, Euclid's study of three-dimensional space (*Elements* XIII.15) continued to be copied and studied. While the term "modular design" is nowhere to be found in Byzantine texts, the comparable concept *monad* (i.e. unit) is common; by multiplying monads, one can form larger groups such as the dyad, triad, and decad.[41] As Heron of Alexandria (1st c. AD) stated in his book on calculating volume: "In order, then, not to have to name feet or cubits (πόδας η πήχεις) or their parts in each measurement, we will exhibit our numerical results as *monads* (μονάδων), for it is open to anyone to substitute for them whatever measure he wishes" (*Metrics* III.A.6). Heron's work would be furthered in the Byzantine period with the publication of the book *Stereometrica* which

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[37] Ousterhout 2008, 70-75; McKenzie 2008, 323.

[38] For example, Frontinus was not only a patrician and a politician (Roman consul and British governor), but an administrator of the water supply; in order to serve in this capacity he had to be adequately educated. As Charles Bennett suggested, his work indicates he was very familiar with the writings of Heron of Alexandria and perhaps was, in fact, educated in Alexandria (1925, xi-xii). There is no reason to assume discontinuity between the Roman and Byzantine periods regarding the need of formal education for both engineers and those who administered the water supply of Constantinople (Crow et al. 2008, 211-218).

[39] Markopoulos 2008, 785–795; Kazhdan 1991, 2143.

[40] Pingree and Kazhdan 1991, 1313.

[41] Monad is a basic concept in the Greek and Roman theory of numbers (eidos), based on Plato's "Theory of Forms" which was adopted and maintained by Byzantine mathematicians; Klein 1992, 79-99; see the entry for *Eide* (Εἴδη) in the *Suida*, the tenth-century Byzantine encyclopedia.

dedicates a whole chapter on the cubic capacity of a cistern (chapter 48).[42] The celebrated architects Anthemius of Tralles and Isidorus of Miletus were both practical builders and theoreticians. Perhaps one of them authored Book XV, appended in the sixth century to Euclid's *Elements*; this book provides a significant study of the so-called "platonic solids" in which the volume of the cube is analyzed. Similarly, a colleague of Anthemius, the mathematician Eutocius of Ascalon, would dedicate an entire volume to the study of the cube's volume and its relationship to the sphere.[43] Simply put, the study of geometric volume was passed from ancient Greek philosophers to Late Roman Neoplatonists and maintained in Byzantine Constantinople when imperial architecture reached a high level of sophistication.[44]

With that said, it must be mentioned that there was another city, which had a deep tradition in the study of geometry and architectural mechanics—Alexandria, Egypt. Like Constantinople, it also contains hundreds of cisterns; the most monumental examples, are multi-level and built in grid patterns, seemingly based on modular design.[45] Unfortunately, these are difficult to access today and not well-studied, leaving their dates difficult to establish. For the past ten years French researchers have begun to reexamine these; preliminary results of the analysis of the El-Nabih Cistern indicates that it was either built or renovated during the Umayyad period.[46] Clearly Arab architects did not bring concepts of "modular design" from the Arabian Peninsula; instead, they adopted the local principles and architectural forms of earlier Roman and Byzantine builders.[47] At the moment we must leave open the question of whether modular design was developed first in Alexandria and later adopted in Constantinople, or vice-versa.

Another question still remains: why did Byzantine architects prefer groin-vaulted rather than earlier barrel-vaulted designs? One clue could be the wooden trusses that were placed above the capitals in Basilica Cistern (Yerebatan Sarayı) and Philoxenos Cistern (Binbirdirek Sarayı) (**fig. 14**). These formed an elastic grid that allowed the entire structure to move as a whole—from wall to column and from column to column—during an earthquake. Apparently the juncture where the transverse arches spring from the capital was an area that was susceptible to buckling from lateral seismic shocks rather than mere vertical gravity; by linking all the springings with wood beams, at an equidistance from each other, they would settle back into their original space after an earthquake. By comparison, in the El-Nabih Cistern (Alexandria) a similar network of stone lintels (lateral buttresses) functioned in a similar manner. Additionally, as Vincenzo Ruggieri proposed, the "standard unit" of Byzantine construction—the square bay capped by a dome—was better suited to withstand seismic forces than wooden-roof basilicas and barrel-vaulted structures since lateral forces are spread out radially from the center of the dome; adding

[42] McKenzie 2008, 323.
[43] Scriba et al. 2015, 100-101.
[44] Downey 1946, 99-118; Downey 1948, 197-200; Klein 1992, 10-25; Tihon 2008, 803-810; McKenzie 2008, 322-328. The dichotomy between practical measurement and theoretical math was never exclusive. For example, Byzantine historians maintained the tradition that the philosopher Socrates was trained as a stonecutter and a son of a stonemason. Socrates would pass his knowledge of the platonic solids to his pupil Plato; see the entry for *Socrates* (Σωκράτης) and Theaetetus (Θεαίτητος) in the *Suida*..
[45] Commission des sciences et arts d'Egypte 1818, 56; 1822, plates 36-37.
[46] Borel and March 2007, 85-92; Borel 2011, 21-30.
[47] Tkaczow 1993, 63, 90, 142.

to this, I suggest that the groin-vault and domical vault on a square bay are alternative versions of this "standard unit" and behave the same way.[48] As mentioned above, the Roman Loutron might have been damaged by an earthquake, so it makes sense that an improved, seismic-proof design was necessary for its Byzantine reconstruction.

Modular Design & the Vaulted Bay

The term *square schematism* was coined by architectural historians as a kind of shorthand to explain design principles that undergird the early medieval architecture of Western Europe.[49] The use of rulers, ropes, compasses, grids, quadratures, set-squares, or try-squares all belong to the development of square schematism; however, there is growing criticism of this concept, especially if it is applied to all medieval structures in an over-generalized fashion. For earlier monuments, few scholars deny that the relationships between the square, circle, and triangle—basic concepts in Euclidian geometry—are found in monumental Late Roman and Early Byzantine architecture.[50]

Beginning with the Romans, round arches become the key proportion that determines both the horizontal length of intercolumniations and the vertical height of the span; clearly this relationship can be abstracted as a two-dimensional half-circle over a rectangular space. As such, the Roman colonnade is a series of modular units, structurally stable while rhythmically composed. This is demonstrated by the Roman elevation sketch discovered at the Pola Arena (Pula, Croatia), which was inscribed on an arcade pier and dates to the last quarter of the first century AD (**fig.19**).[51] This sketch displays that the extrados circumference was the main modular unit that determined the span and pier width; its lowest point (which bisects the span) is the center point for a larger circular measurement of a compass (**fig. 20**). The circumference of this larger circle determined the lower storey's springing line; this is implied by the similar lines of the springers in the upper storey (**fig. 21**). Thus, Roman architects, by using the square grid and compass in both ground plans and elevations, necessarily abstracted their structures in terms of the cube and sphere. Later in Byzantine architecture, this correlation is manifested in a three-dimensional manner; that is, the development of the spherical dome over a cubed space becomes a "standard unit" or module reinforcing the relationship between circle and square.[52]

Surely the relationship between the square, the human body, and architecture was first realized in ancient Egypt. Many examples of unfinished Egyptians artworks survive that still have their square grids visible. These apply a canon of proportions to the human body; moreover, Egyptian drawing boards exist, which were like rulers or guidelines based on the set-square.[53] Likewise, the square grid was apparently applied to ground plans of buildings and complexes such as Imhotep's mortuary complex for Pharoah Djoser (2667-

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[48] Ruggieri 1991, 141-152.
[49] Bucher 1972, 37-51; Horn 1975, 351-90;
[50] Stricevic 1993, 79-80; Stalley 1999: 116-119; Fernie 2002, 1-9.
[51] Gnirs 1915, 41 and fig. 17; Haselberger 1997, 82 fig. 7.
[52] Krautheimer 1986, 242 and 244.
[53] Iversen 1975; Lorenzen 1980, 181-199.

2648 BC).[54] The idea might have passed on to the Greeks and eventually manifested in the theories and constructions of Hippodamos of Miletus (5th c. BC). The use of standard proportions and, in turn, *symmetria* seems apparent in the design of the Parthenon,

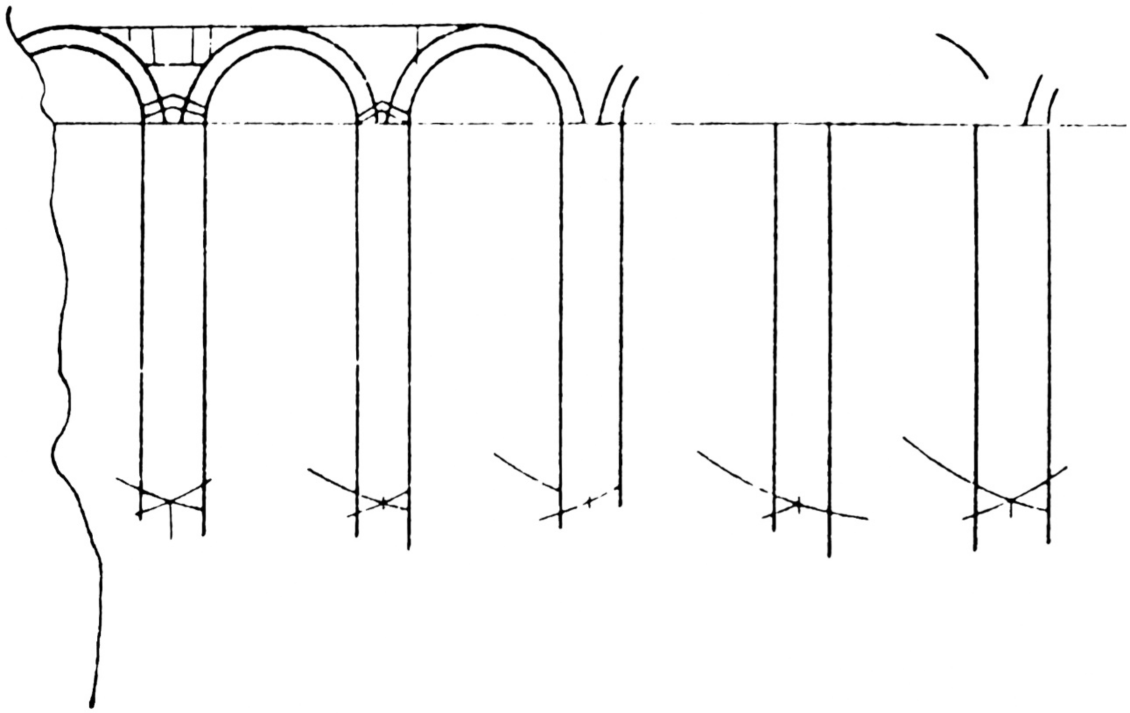

Fig. 19. Drawing of the elevation plan (inscribed on marble) of the Pola Arena arcade, last quarter of the 1st c. AD (from Gnirs 1915, fig. 17).

[54] Rossi 2004, 81-95, 122-130.

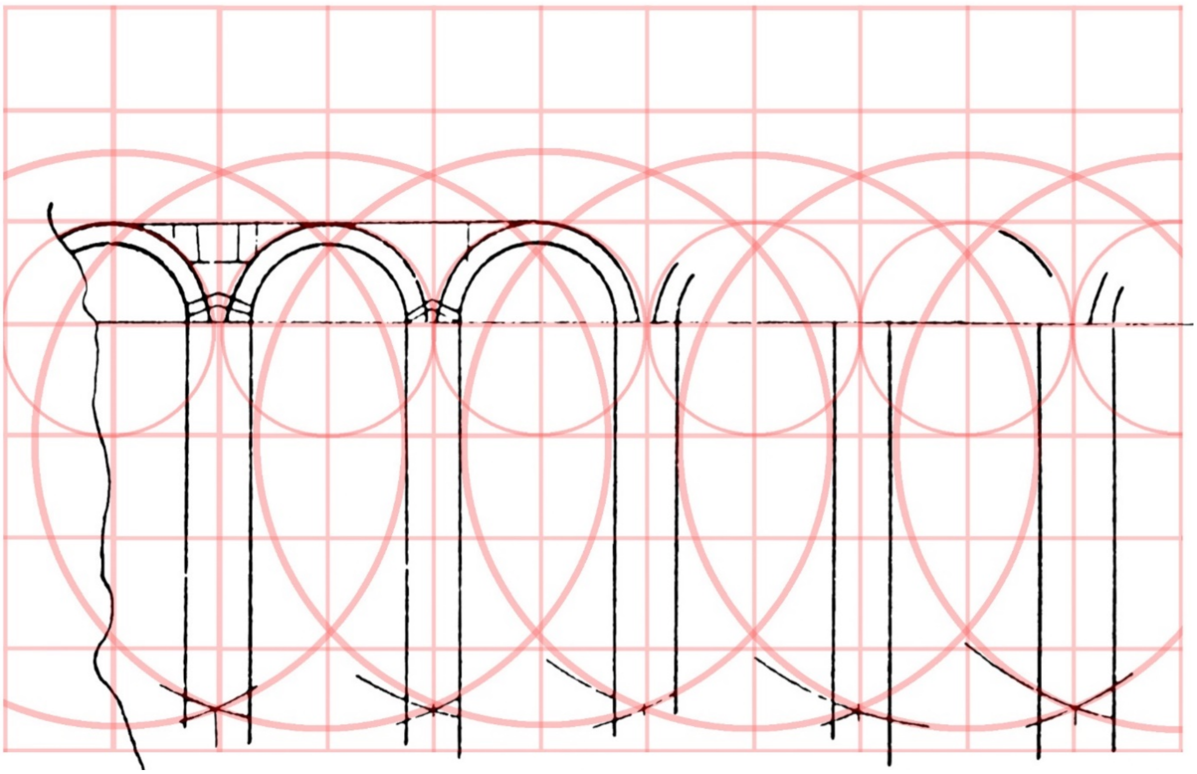

Fig. 20. Drawing of the elevation plan of the Pola Arena arcade with a square grid imposed, indicating how a compass was used for measuring proportion (author).

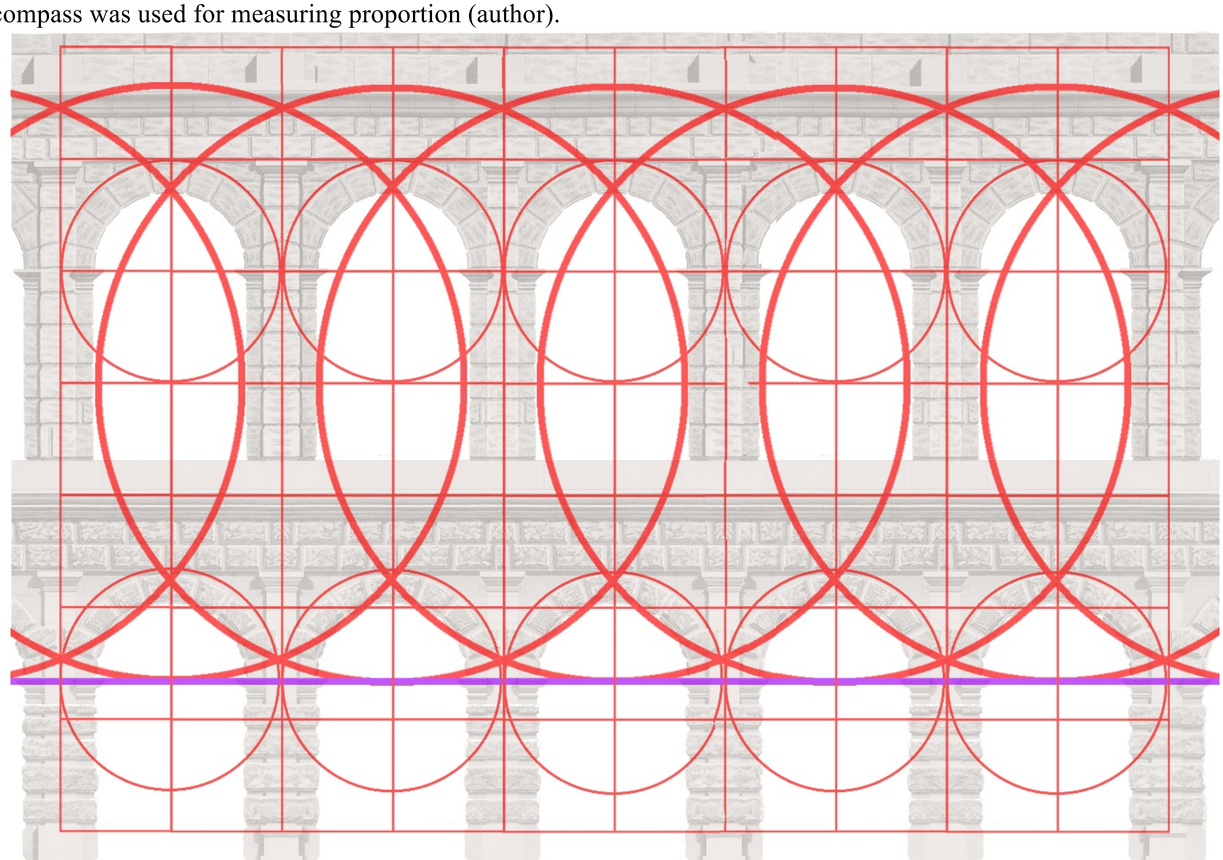

Fig. 21. Diagram illustrating how the Pola Elevation Sketch reflects the actual proportions of the Pola Arena's second and third storey (reconfigured by author, based on the illustrations in Stuart and Revett 1816, vol.IV. Chapt. 1.Pls.IX and XI). Purple line indicates springing line of the second storey's arcade.

related to Polykleitos' *Canon* (of proportions).[55] Evidently in the Hellenistic period, square grids were employed in laying out massive temples and other public buildings; as J.J. Coulton stated, "the modular system of proportions would make it easier to plan accurately beforehand…the change in the whole emphasis of architecture…required something more profound."[56] This tradition was inherited by Roman architects, if we assume that Vitruvius represents common Roman practice; for example, the Pola Arena (as discussed above) and the elevation of the Temple of Portunus (early 1st c. BC), which was based on the square dimensions of the cella ground plan.[57] Roman ideas of architecture would spread throughout Europe, North Africa, and western Asia and into the Byzantine and Early Medieval periods.

The architectural plan of St. Gall was drawn around the year 817, commonly associated with Haito, Bishop of Basel, who either drafted it or commissioned its creation. Based on its format, Walter Horn (chief among others), developed the idea that modular design and square schematism was an innovative element of Carolingian architecture.[58] Horn argued that the crossing-square of the St. Gall basilica was the main unit from which all the other structures were measured—according to the plan. Most historians of medieval architecture agree that this square unit would influence modular design in subsequent periods, especially the formation of bay systems in Romanesque vaulted churches; Richard Krautheimer, who was well aware of the research of the St. Gall plan, agreed with these ideas and applied similar terminology to Byzantine architecture.

Curiously, Walter Horn emphatically disassociated the St. Gall plan and its bay system from earlier Byzantine bay designs. Instead he argued that "modular concepts" were developed by Carolingian architects who based their work chiefly on Early Christian forms which, he deemed, were actually "anti-modular."[59] Based on a theory by Josef Strzygowski, Horn further proposed that the origins of bay system could be found in northern European timber-hall construction.[60] This suggestion is unpersuasive for many reasons: first, no pre-Carolingian timber-hall survives for scholars to assess its superstructure; second, size of timber-frame bays varies depending on the tensile strength of the wood used rather than aesthetic or geometric principles; and third, Roman and Byzantine vaulted bays predate the timber structures referenced by Horn.

Horn dismissed the vaulted churches of Syria because they were too irregular and too far from St. Gall to have influenced Carolingian building methods. From these observations, he seems to have over-generalized the development of Byzantine bay design; thus he overlooked the sixth- through seventh-century vaulted churches of southern Turkey, Armenia, Georgia and Cyprus as well as Byzantine cisterns and reservoirs. In these

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[55] Pollitt 1972, 106-7; Haselberger 2005, 106-8.
[56] Coulton 1977, 69-71; Haselberger 1997, 77-94; Senseney 2007, 555-595.
[57] Jones 2000, 33-43, 64-68.
[58] Horn 1958, 2-23; 1975, 351-90; Horn and Born 1966, 285-308.
[59] Horn 1975, 351-90, especially, 374, 386, 388.
[60] Horn 1958, 2-23; recapitulated in 1975, 386-387.

and later Romanesque and Gothic churches, their bay systems are inextricably based on groin-, barrel-, and domical-vaults; obviously, any similarities that vaulted bays have in common with wooden-roof structures was cosmetic and superficial. While it is difficult to provide direct evidence for Byzantine influence on Carolingian architecture, there are sufficient reasons to explore the possibility.[61] Even Walter Horn acknowledged that Bishop Haito visited Constantinople and would have seen Byzantine vaulting.[62] As this chapter proposes, Byzantine architects first developed the vaulted-bay system in cisterns and reservoirs prior to the practice of groin-vaulting churches; therefore, cisterns occupy an important interval in architectural history, between the Roman barrel-vaulted cisterns and the bay system of cross-domed churches, like early ninth-century Dereağzī (near Demre, Turkey).[63]

Further Thoughts

The title of this book, *Against Gravity*, implies that as architects build upward, they struggle against gravitational forces that keep us human beings grounded. This predicament was eloquently penned by the French novelist Joris-Karl Huysman:

> I reserve my opinion, indeed, as to the accuracy of [Jules] Quicherat's declaration that "the history of architecture in the Middle Ages is no more than the history of the struggle of architects against the thrust and weight of vaulting," for there is something in this art beyond material industry and a problem of practice; at the same time he is certainly right on almost every point.[64]

We, architectural historians, can sympathize with this notion since we dedicate our lives to studying matters where art meets science or, in Byzantine terms, where technology *is* art (τέχνη). Behind every artistic practice lurks a mind; embedded in every ancient edifice there is ancient theory of gravity.

Over the years as I study medieval building practices, I find myself moving away from the modernist perspective of Quicherat, since it does not reflect the spirit of ancient and medieval worldview as Huysman expressed. Early Byzantine architects did not *struggle* against gravity per se; rather, they *harnessed* the power of gravity. Gravity allowed engineers to move water thousands of miles in aqueducts all over the Empire, while the knowledge of hydraulic pressure, based on gravity, allowed *castellum divisoria* and reservoirs to distribute water to various parts of the Byzantine city; in turn, these structures filled the baths, powered water mills, fountains, baptisteries, etc. Additionally, architects harnessed the power of gravity when they built their vaults, since both round

[61] For example, see the studies of Porter (1912, 161-169); Krautheimer (1942, 1-33); Kleinbauer (1965, 2-11; 1988, 67-79); Stalley 1999, 67-81; McCormick 2011.
[62] Haito was impressed by Constantinople since he wrote of his journey in a book called the *Hodoeporicon*, which, unfortunately, does not survive; Horn 1975, 373.
[63] Krautheimer 1986, 226, 238-240, 283-287; Morganstern 1983.
[64] The French original is: "Je fais bien quelques réserves sur la justesse de cette boutade de Quicherat 'que l'histoire de l'architecture au moyen âge n'est que l'histoire de la lutte des architectes contre la poussée et la pesanteur des voûtes', car il y a autre chose, en cet art, qu'une industrie matérielle et qu'une question pratique, mais n'empêche qu'il a certainement raison sur presque tous les points"; Joris-Karl Huysmans, *La Cathedrale* (1898), Chapter III.

and pointed arches need gravity to lock the voussoirs and archivolts into a coherent stable system. From pyramid builders to contemporary engineers, the one thing that unites the broad gamut of architectural history is the mastery of gravity. In fact, one thing we learned from the construction of the International Space Station beginning in 1985—perhaps the most expensive piece of architecture in history—is that it is impossible to construct a building completely in outer space because of microgravity; yet, our impressive understanding of universal gravity allows such a station to orbit the planet.[65]

In human experience gravity and water cannot be separated. Previously I argued that pointed arches and flying buttresses were being used systematically in the early seventh century on the island of Cyprus; *nota bene*, these innovative forms appeared together in the waterworks belonging to the same renovation phase within the same city.[66] So, in these Cypriot monuments, apparently the idea of channeling water was paralleled by the theory of channeling gravitational thrusts. Naturally, this pairing of water and gravity leads to the question: Was it more than happenstance that the Gothic flying buttresses functioned both as a means to channel rainwater away from a building and to provide lateral support? I leave it to Gothic specialists to answer that question; nevertheless, it is hardly coincidental that the incremental development of external buttressing for purpose of supporting spacious interior vaults can easily be traced from Roman baths and cisterns to Byzantine basilicas and reservoirs.[67]

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[65] Harland and Catchpole 2002, 189-206.
[66] Stewart 2012, 13-14; Stewart 2014b, 1-29.
[67] Stewart 2014b, 19-23.

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