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Hydraulic Characteristics of the Drainage Systems of Ancient Hellenic Theatres: Case Study of the Theatre of Dionysus and its Implications

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Abstract

The content of this article provides interesting history, facts and information about the drainage systems of ancient theatres in mainland Greece and Asia Minor from prehistoric times till the Hellenistic period. This study comprises representative examples of drainage systems in theatres at Knossos, Phaistos, Dionysus in Athens, Arcadian Orchomenos, Ephesus and Delos. Moreover, what we aim to demonstrate is that these drainage systems represent evolutionary techniques and principles that can still be used today in order to avoid wasting water resources. Moreover, these techniques may prove attractive for the development of sustainable strategies to counter mounting problems, especially of a socio-economic nature. In addition, the article presents evidence for the conception that adaptations to individual environmental and hydraulic characteristics of specific locations were considered in relation to drainage systems of ancient theatres. Thus, through a case study of the carrying capacity of drainage channels at Dionysus' theatre at Athens, the sustainable nature of this construction is demonstrated, including its capacity for management of storm water.

Keywords:

Delos; Dionysus; Drainage systems; Ephesus; Epidaurus; Hydraulic models; Historic buildings; Green buildings; Knossos; Orchomenos; Phaistos

Prolegomena

The modern word *theatre* derives from the Greek word *θέατρον* (pr. *theatron*) meaning "*place for seeing*" (Liddell, Scott, Jones & McKenzie, 1996). As a type of building, the Greek theatre is quite well defined, at least in the late Classical and Hellenistic (*ca*. 400-31 BC) periods, when the canonical architectural form of monuments had been fully developed. Almost all of the 251 monuments classified as theatres share the following defining characteristics: "a building that consists of a monumentalised 'koilon' of canonical semicircular design, reflected in the shape of the 'orchestra' as well as of other details like stone seats and stairways, 'proedria' and 'euripus'" (Frederiksen 2002).

The Archaic and early Classical periods of Greek history, present a problem in relation to certain identification, first of all because remains of scene buildings are lacking, or at best debatable; as the same applies to drainage systems. In prehistoric times (e.g. the Minoan and Mycenaean Ages in Greece), it appears that something equivalent to the 'theatron"' of later periods existed; clearly, however, the drainage systems of these early structures were not well defined. Nevertheless, in the Greek Classical and Hellenistic Ages, the drainage system was a substantial component of each theatre.

This study discusses the evolution of major achievements in the scientific fields of drainage systems in the ancient Greek theatres of the Archaic through the Hellenistic Age, with emphasis on the development/evolution of significant technologies through the centuries. Valuable insights into the technologies and management of ancient drainage systems of theatres, including their apparent characteristics of durability, adaptability to the environment and sustainability, are provided. These technologies underpin modern achievements in water engineering and bear witness to the saying so often cited in the scientific community: "*Probing the past and facing the future*". (Meredith 2001 and Angelakis *et al.* 2013).

A typical design of an ancient theatre (Epidaurus, from the end of the 4^{th} century BC), with a schematic layout of its elements and with a quite common structural layout of the main drainage system, is shown in Figure 1.

At this point it is relevant to mention that the Roman architect Vitruvius (*ca.*15 BC) listed guidelines for maintenance of drainage systems of ancient walks: *5.9.7.* "*That they may be always dry and not muddy, the following is to be done. Let them be dug down and cleared out to the lowest possible depth. At the right and left construct covered drains, and in their walls, which are directed towards the walks, lay earthen pipes with their lower ends inclined into the drains. Having finished these, fill up the place with charcoal, and then strew sand over the walks and level them off. Hence, on account of the porous nature of the charcoal and the insertion of the pipes into the drains, quantities of water will be conducted away, and the walks will thus be rendered perfectly dry and without moisture.*"

From this excerpt it is obvious that the engineers of the Roman period understood very well how to incorporate drainage facilities in their constructions. Undoubtedly, this reflects older knowledge accumulated over past centuries in the Greek world about the necessity for adequate drainage facilities (e.g. Strabo *ca.* 23), and thus clearly indicates the construction philosophy behind these structures.

Moreover, the drainage system of Dionysus' theatre in Athens, situated on the south slope of Acropolis, will be examined as a case study in order to determine whether the drainage system of this theatre could exceed its carrying capacity. Thus, studying the drainage system of the theatre of Dionysus will provide better understanding of the 'mechanics' and design philosophy behind ancient Greek water management and engineering.

As for materials, archaeological findings indicate that stone conduits as well as clay pipes were used to carry wastewater out of the houses and into the ground, and that toilet facilities were flushed with water into a sewer system under the streets (Apel 2004). However, as will be illustrated on the basis of the cases of theatres mentioned in this paper, this drainage system was based almost entirely on conduits built from stone blocks or cut into the natural rock.

Pre-historic times (*ca.* 7,000 – 1,100 BC)

During the Neolithic Age (*ca*. 5,700-3,200 BC), the first successful efforts to control the water flow were driven by the need to expand food production (such as dams and irrigation systems), e.g.in Mesopotamia and Egypt. The first successful effort in mainland Greece to exercise wastewater and storm water management was undertaken during the Bronze Age.

According to Angelakis *et al.* (2005), in the entire structure of the Minoan palace (Crete, Greece) there appears a remarkably elaborate sewerage system running through the domestic quarters and adjoining halls.

A certain example from this period is the open, north-western, area of the palace at Knossos, originally described as the 'theatre' by Evans. This structure is now considered to have been a site reserved for religious activities and performances (Panagiotopoulos & Günkel-Maschek 2012). It is a platform with rows and steps, formed as an angle-shaped, open area. At the bottom of the steps begins a narrow raised road that divides a paved court. Evans believed that the court was used for ceremonies, watched by standing spectators. The raised paved road, known as the Royal Road and considered to be the 'oldest road in Europe', continues in the opposite direction.

The Royal Road appears to be a Late Minoan reconstruction of an earlier pavement (Driessen and Schoep 1995) and it connects the palace (the theatre area), the House of Frescos, the town and the Little Palace (Fig. 2a). It is very well paved with stone slabs and, on either side, cement wings and drains (Pendlebury 1963).

A similar place known as – or named – 'theatre' (Fig. 2 b) appears at the palace of Phaistos (Crete, Greece). As indicated, there was a well designed drainage system in these Minoan palaces. Compared to later Classical constructions there is, however, no specific drainage system incorporated into Minoan theatres, and the runoff was flowing directly to the central drainage and sewerage systems of the palaces or/and the roads.

Historical times

Archaic and Classical Greece (*ca*. 630-323 BC)

It is well known that the theatre as a construction originates from ancient Greece. The first theatres of the archaic period – and original phases of well-known ones, including Delos (Fraisse & Moretti 2007) and Dodona (Antoniou 2014) – were formed by wooden plank benches (Papastamati-von Mook 2011), placed on a sloping hill, with a floor space in front of them where the performances took place. Until *ca*. the mid-fifth century BC, the dramatic and musical contests at Athens were held in the Orchestra of the Agora, which was surrounded by wooden stands or bleachers for the spectators (Travlos 1971).

The Greek theatres were often built outside urban areas or adjacent to important sanctuaries. Their usual situation on a hillside offered an easily adaptable structure to the natural ground. Originally, they were not designed as monumental structures, but exclusively as functional ones. A typical, longitudinal cross-section of a theatre, is shown in Figure 3, where it can be seen the position of the drainage channel, called ‘euripus’.

That drainage channel was running around the edge of the orchestra and in most examples was not covered. Quite often when the duct was deep, thick stone slabs covered it over the extensions of the stepped corridors, as in the Athenian Dionysus theatre (Fiechter 1935) and at Dodona (Antoniou 2014). In cases where the orchestra was completely or partially formed on the rocky subsoil, the duct was cut into that rock (Fig. 4). The outwards underground path was directed mostly to the building of the scene, either passing by (Fig. 1), or under it (Fig. 6).

The variety of forms of drainage (Broneer 1936), along with the diversity of cross sections of varying sizes, thus different carrying capacities, is worth studying in comparison to the geographically relevant hydrological data.

The Theatre of Dionysus

The theatre of Dionysus in Athens (Fig. 5 a & b) dates back to the middle of the 6th century BC, during the 10th Ancient Olympic Games. The theatre was situated on the flattened terrace above the temple of Dionysus, thus situating the spectators on the gentle slope beneath the south side of the Acropolis (Travlos 1971). In the *ca.* 5th century BC, the site was provided with a supposedly rectangular wooden structure (Papastamati-von Mook 2014), while the major reconstruction of the theatre in stone took place in the *ca.* 4th century on the initiative of the statesman Lycurgus (Papastamati-von Mook 2011). The capacity of the theatre is 30,000 seats. It is divided into two staggered rows. The first has 34 rows of seats and the second 21 (Fibonacci numbers). The angle between the main theatre and the scene is 222.5° / 137.5° = 1.618, better known as golden ratio'the golden ratio' (or number "φ"). In addition to that, the average of the ratio of stairs (34 + 21)/ 34 = 1.619 and the ratio of rows 34: 21 = 1.617, approximate 'φ'.

In this theatre, the drainage channel collected the rainwater from the large "cavea" or "koilon" (place of seats) and the orchestra, leading it through an extended sewerage system to the south-east side of the Acropolis hill (Fig. 6). The deep canal (1.06 m deep and 0.96 m wide, Fig. 7) was built of carefully assembled, large blocks of coastal lime stone from Piraeus, and was drained under the stage of the theatre (Fig. 6a) to the south (see also Fig. 8).

The Theatre of Arcadian Orchomenos

The theatre of Arcadian Orchomenos (Fig. 9) was built in the 4th century BC and was in use until late Roman times. Because of the steep natural slope on which it is built, the theatre had a drainage system for rainwater (Petropoulos *et al.* 2008). At the southern part of the 'koilon', a constructed rainwater drainage channel remains, the total length of which is 22.7 m and the width 1 m., following the slope in the direction from west to east. It begins at the top of the 'koilon' and ends near the stage of the theatre. It is entirely built from local, processed limestone plinths.

Hellenistic Greece (*ca*. 323-76 BC)

Later, during the Hellenistic period, further developments were made in hydraulics, such as the construction and operation of aqueducts, cisterns, wells, harbours, water supply systems, baths, toilets and sewerage and drainage systems. During that period, the political and economic situation changed, leading to much more architectural development and urban beautification, in which the hydraulic constructions played a major role (Mays 2008).

The Theatre of Ephesus

One of the better examples of this period is the Great Theatre at Ephesus (Fig. 10) in Asia Minor, in present Turkey. This theatre, which was the city's largest and most impressive building, had a seating capacity of 24,000 spectators.

The theatre was built in the Hellenistic period and has a notable drainage system as it can be seen in Fig. 10) (Mays 2004), which led the stormwater to the drainage system of the town– something that can be assumed from the topography of the surrounding area (see also Ortloff and Crouch 2001). Thus, it is thought that the one branch (in the west) was drained into the sewer of the 'Harbour Street' and the other (in the south) into the sewer of the 'Marble Street'.

The Theatre of Delos

The ancient theatre of Delos (a small, nowadays uninhabited, island in the Aegean Sea) is one of the few that were built entirely of marble (Fraisse & Moretti 2007). Its construction started around 314 BC and ended around 70 years later, in *ca*. 250 BC. In 88 BC, the theatre, which had a capacity of up to 6,500 spectators, was abandoned, along with the famous sanctuary and town of Delos, after King Mithridates' invasion of the island.

Delos was one of the most important religious centres of ancient Greece, an island in the Cyclades, where Apollo, god of light, and Artemis were born according to mythology. It is no coincidence that the centre of the theatre, the orchestra, is considered to be the brightest point in the Mediterranean, according to a study conducted by the University of Athens (ANSAmed 2012).

As can be seen in Figures 11 a and b, there was a perimetric, open channel, built from the same material as the theatre, which collected the rainwater and drained it to a large vaulted cistern (Fig. 11c) (Fraisse & Moretti 2007) situated 200 m west and downwards from the theatre, in order to store and consequently supply water for any purpose on this dry and barren island, and mainly for the '*Quartier du Theâtre*' (Neighbourhood of the Theatre). It should be mentioned that the impressive mansion houses of Delos had their own rainwater cisterns to satisfy their demand.

Hydraulic analysis: a case study of the Dionysus theatre

This section will zoom in on the hydraulic characteristics of the Dionysus theatre in Athens (the Lycurgan 'version' from the late Classical period), since it is considered to be one of the most notable cases of theatres from the classical period. As mentioned above, in this theatre the drainage channel collected the rainwater from the large cavea and the orchestra and also from certain areas of the south slope of the Acropolis. According to Frazer (1913), the orchestra is divided from the seats of the auditorium by a parapet composed of upright slabs of marble 1.09 m high. Along the inside of this parapet, separated by it from the seats, runs a broad gutter of limestone 0.89 m in width. This gutter was originally open except that opposite the vertical passages, which lead through the tiers of seats, it was bridged with slabs of limestone. In later times it was covered with marble slabs. The function of this gutter, which forms part of the original building, was to drain off the water from the auditorium; however, this function was frustrated by the erection, at a later time, of the marble parapet, which divides the orchestra from the auditorium. The parapet and the marble covering of the gutter belong, according to Dörpfeld (1896), to the beginning of the third century A.D.

The storm water was led through an extensive sewerage system, to the south-east side of Acropolis hill (see Fig. 6), where it was possibly reused in workshops. This point of view might be verified by the extensive excavations carried out in the nearby area (Makrigianni neighbourhood) during the process of creating the foundations for the contemporary New Museum of Acropolis (of nowadays).

In the Hellenistic period, a workshop was established where the courtyard of the New Museum of Acropolis is today, with a system of three connecting rectangular tanks, arranged on different levels. A pipe drained water into an underground cistern, while the foul or surplus water was removed to the nearby road through a built drainage channel. The workshop was probably a fullery or washery of some form (Pitt 2011). It is also believed that south-west of the theatre there were some copper workshops (Kalligas 2011). The rest of the wastewater was diverted to the Ilissos river outside the city walls, following the topographical strands of the area (Fig. 12).

From the outset, according to Kolobova (1961), the drainage channel was situated around the semicircle orchestra; later on it was moved underground, passing under the skene in a south-easterly direction. Its width ranged from 0.91 to 0.96 m, while the depth ranged from 0.87 to 1.10 m.

According to Dörpfeld (1896), who also carried out further excavations in the area, the deep canal (1.06 m deep and 0.96 m wide, Fig. 7) was very carefully built of large blocks of coastal lime stone from Piraeus and was drained under the stage of the theatre (Fig. 6a) towards the south, where it was covered with slabs of Hymettus marble.

In this case study, further calculations are conducted to verify the carrying capacity of the drainage system of this theatre, using the typical dimensions of the channel provided by Dörpfeld (1896), since he designed accurate figures and topographical diagrams that can provide enough information to facilitate the calculation process, which can be seen in detail in the Appendix.

Based on the results of the calculations, comparing the peak discharge rainwater Q_p with the discharge capacity that derives from Manning's equation (Q_{max}), we can conclude that $Q_p \ll Q_{max}$. Thus, it can be concluded that the channel was designed to accommodate rainfall beyond what was necessary; i.e. it was overdesigned according to modern design criteria.

At high flow rates, the velocity and shear stress are high and may cause gradual erosion of the channel. Probably, that is why the construction material was limestone, since it is a sedimentary rock composed largely of the minerals calcite and aragonite, which are different crystal forms of calcium carbonate ($CaCO_3$).

The solubility of limestone in water and weak acid solutions leads to karst landscapes, in which water erodes the limestone over thousands to millions of years. Limestone reacts chemically with hydrogen ions in water, but it is, in general, resistant to water. However, it is important to note that the more acidic the water is, the more the limestone will react and erode.

Conclusions

Ancient Greek theatres were always built on hillsides and they were often situated outside cities. The ancient architects usually used open channels, made of stone ('euripus') or other local materials, and in this way, with the help of the drainage system, the wastewater coming from rainfall could be disposed of in the nearby countryside, directly or through a local sewer network, or it could be stored in reservoirs for multiple purposes. This fact, if examined on the basis of the criteria of our era, can be viewed as a primitive enrichment system of aquifers or as a well-planned system for reusing drainage water (e.g. the theatres of Dionysus and Delos). This should be seen in light of the fact that the eastern part of Hellas always had low rainfall and, furthermore, conserving water remains a necessary procedure today.

As has been seen in this case study, the dimensions of these drainage channels had a satisfactory carrying capacity. It can also be claimed (after further study) that the planning of the Greek theatres and their drainage systems adhered to the principles of 'sustainability', a characteristic principle of environmental planning today, as well as a concept very commonly used in the scientific community (e.g. United Nations 1987; Adams 2006; Lélé 2001; and Buchenrieder & Göltenboth 2003).

The present article argues for the case that the scientific community today would benefit from studying the good examples and construction guidelines of the past, which may still be useful in current and future projects.

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Appendix

The flow rate of rainwater and wastewater is calculated here using the so-called Rational Method. The calculation of the draining areas is made using the maps of the Hellenic National Cadastre & Mapping Agency S.A. (available at: http://gis.ktimanet.gr/wms/ktbasemap/default.aspx). The upper area (A.1) is calculated to be 2,270 m² (or 0.00227 km²) and the lower area (A.2) 7,992 m² (or 0.00799 km²) (total area A_t = 0.01026 km²) (see Fig. 13).

The time of concentration (t_c) is estimated to be approx. 5-10 min. According to modern design practice, the return period for such a channel would be 10 years, but for illustration we test a much higher value, T = 10,000 years, similar to that being used in dam designs. We also apply the lowest value of time of concentration t_c = 5 min = 0.083 h, which corresponds to highest rainfall intensity. Using the intensity-duration-frequency formula for Athens (Asteroskopeio) (Koutsoyiannis 1993, Table 3.1, p. 39), an estimate of rainfall intensity is:

$$i\ (\text{mm/h}) = 207\ (10{,}000^{0.15} - 0.61)/(1 + 0.083/0.17)^{0.77} = 513.78\ \text{mm/h}\quad (\text{Eq.1})$$

At this point we need to check whether or not the estimation above (which is based on present day data) is representative for the years of antiquity. According to Krasilnikoff (2013), the average rainfall in ancient Athens proper is estimated to be 300 ~ 400 mm/y, which is more or less the same as that estimated from recent data. Thus, it can be assumed that the above is representative for ancient times too.

The Peak discharge Q_p for rainwater is calculated using the Rational Method:

$$Q_p = C\ i\ A \quad (\text{Eq. 2.a})$$

where C is the runoff coefficient, i the rainfall intensity (97.4 mm/h) and A the drainage area. As shown in Figure 12, there are two distinct contributing areas, i.e. the area A_1 = 2,270 m² and the area A_2= 7,990 m². According to Koutsoyiannis (2011) it can be assumed that C_1 = 0.5 (for the slope of a hilly area) and C_2 = 0.85 (for a stone-covered area).

Thus:

$Q_p = (0.5 \times 2270 + 0.85 \times 7990) \times 513.78 \times 10^{-3} / 3600 = 1.13\ m^3/s$ (Eq. 2.b)

The discharge capacity of the channel will be calculated, using Manning's equation for the open channel flow with rectangular cross section with dimensions D = 1.06 m (depth) and W = 0.96 m (width; see Fig. 7).

The cross section area is 1.06 × 0.96 = 1.018 m², the wetted perimeter is 0.96 + 2 × 1.06 = 3.08 m and the hydraulic radius is:

R = 1.018/3.08 = 0.33 m. (Eq. 3)

The channel slope S is estimated from Fig. 14 as:

S = (90.32 – 87.54) / 30 = 0.094. (Eq. 4)

The Manning n coefficient is estimated from tables for channels made of stone (Chow, 1959) at n = 0.035.

Thus, according to Manning's formula:

$V = (1/n)\ R^{2/3}\ S^{1/2} = (1/0.035)\ 0.33^{2/3}\ 0.094^{1/2} = 4.18$ m/s. (Eq. 5)

The discharge capacity is thus, $Q_{max} = 4.18 \times 1.018 = 4.26\ m^3/s$ (Eq. 6), which compared with the peak flow (Q_p), it is ≈3.76 times greater than it.

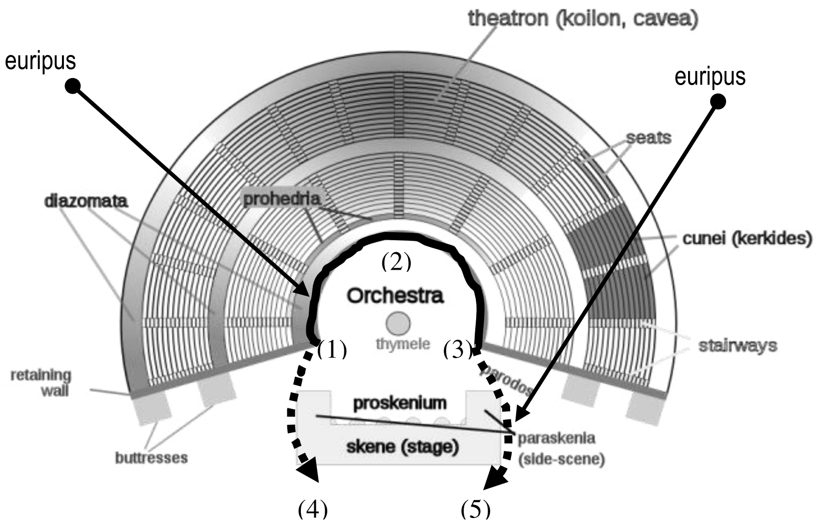


Figure 1. Typical layout of an ancient Greek theatre: Components and common structural layout of the drainage system. The solid coloured line (1)-(2)-(3) refers to the open or covered shallow drain and the dashed lines (1)-(4) & (3)-(5) to the underground drain (plan by Leftezi and Flyax, arranged by K. Kollyropoulos)

(a) (b)

Figure 2. The Minoan theatres: (a) at Knossos and (b) at Phaistos (images by A. N. Angelakis).

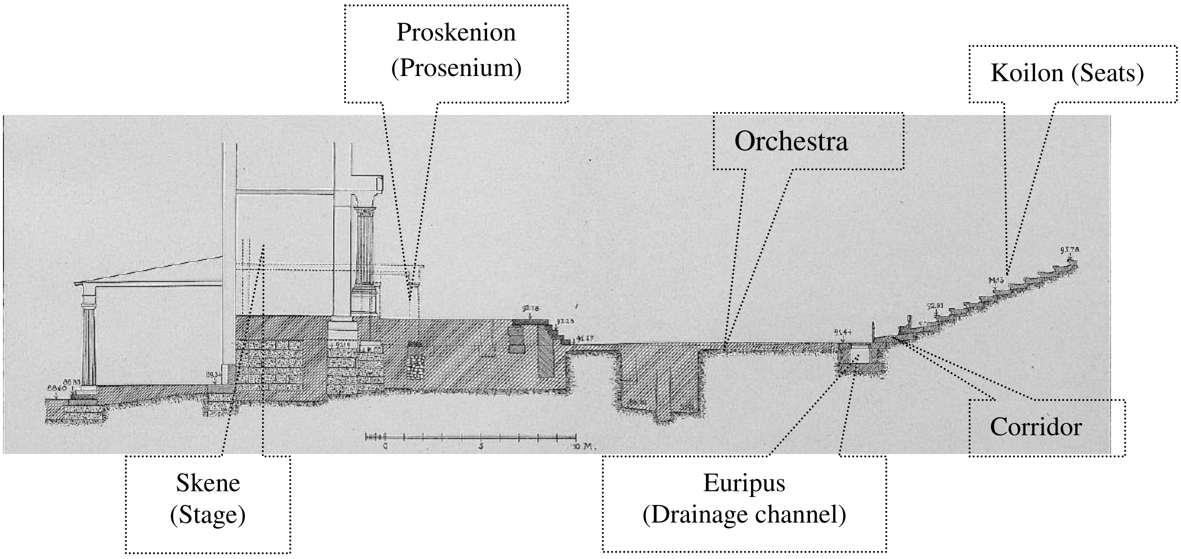
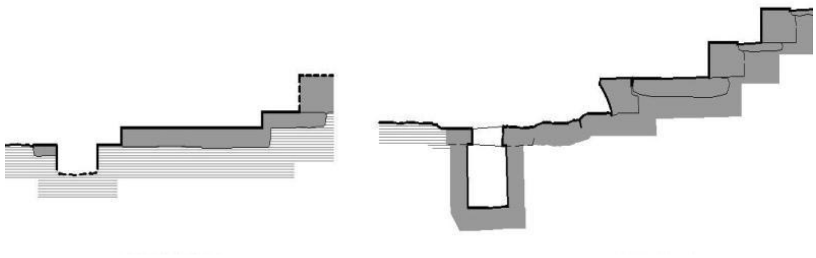


Figure 3. Typical longitudinal cross-section of a Greek theatre (arranged by K. Kollyropoulos on a base drawing adapted from Döperfeld’s plans, 1896)



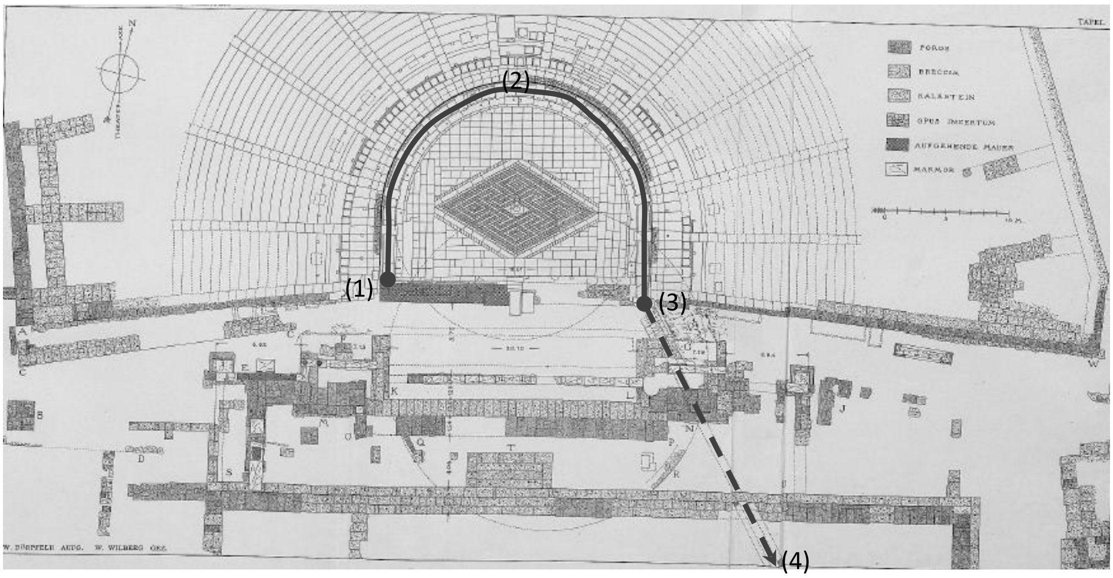
(a) (b)

Figure 4. Sections of drainage channels partially or totally dug in the rocky subsoil at: (a) Piraeus and (b) Dodona (sketches by G. Antoniou).

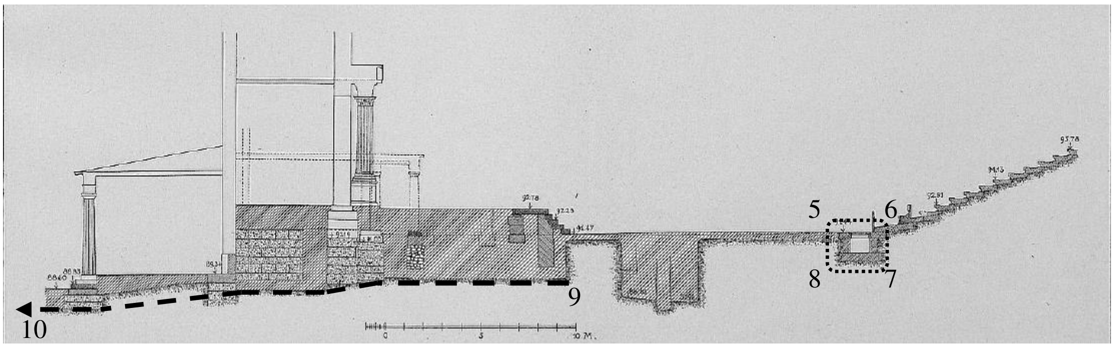
(a)

(b)

Figure 5. The theatre of Dionysus: (a) view from the Acropolis hill with Acropolis Museum to the southwest (image by A. N. Angelakis and (b) its orchestra with part of the drainage system (image by K. Kollyropoulos)



(a)



(b)

Figure 6. The Dionysus' theatre: (a) Ground plan. The continuous line (1)-(2)-(3) indicates the drainage duct - covered at the extensions of the stepped corridors - and in dashed (3)-(4) its underground sewer. And (b) Section of the orchestra and the scene indicating the drainage channel [dotted rectangular (5-6-7-8)] and the sewer [dashed line (9-10)] (arranged by K. Kollyropoulos on a base drawing adapted from Döperfeld's plans, 1896)

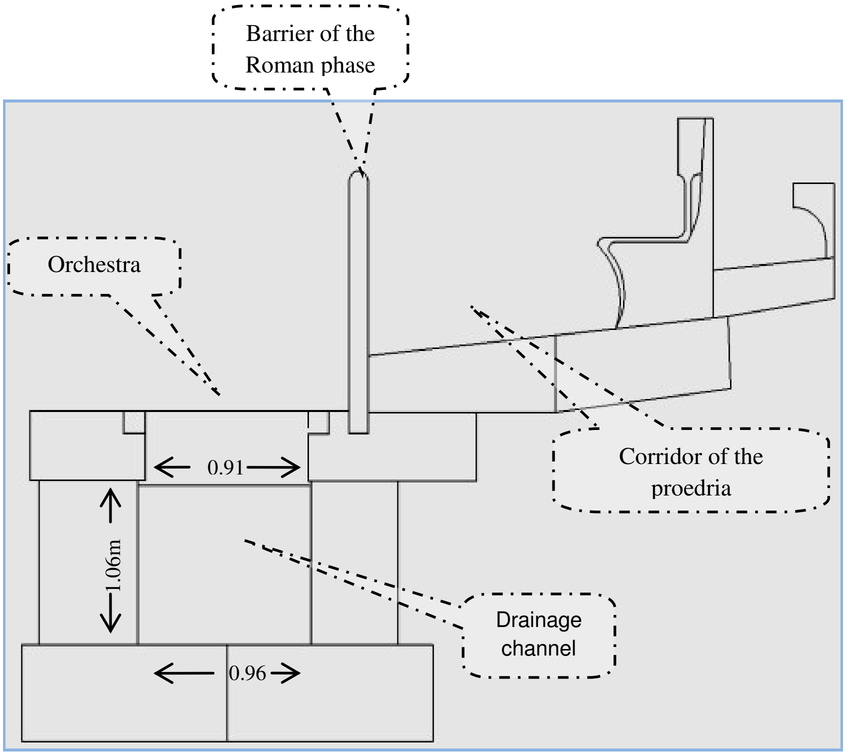


Figure 7. Dionysus' theatre: cross section of the drainage channel and its surroundings (arranged by K. Kollyropoulos on a base drawing adapted from Döperfeld's plans, 1896)

(a) (b) (c)

Figure 8. The Dionysus theatre, details of the drainage channel (images by K. Kollyropoulos) (a) view next to the orchestra, (b) view of the channel exit under the stage of the theatre, and (c) view of the downwards flow of the channel

Figure 9. The theatre of Arcadian Orchomenos (image by Tobias Schorr): general view of the theatre and the drainage channel around and downwards the orchestra

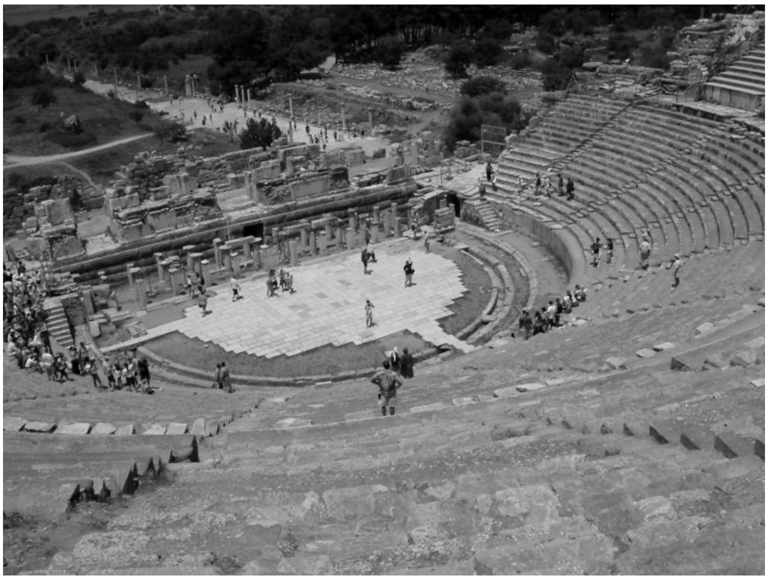


Figure 10. The Great Theatre of Ephesus (image by Radomil): a general view**,** with the drainage channel built in the perimeter of the orchestra

(a) (b) (c)

Figure 11. The theatre of Delos: (a) A general view (image by Bernard Gagnon), (b) the drainage channel of Theatre of Delos (image by Olaf Tausch), and (c) the big cistern of the theatre (image by G. Antoniou)

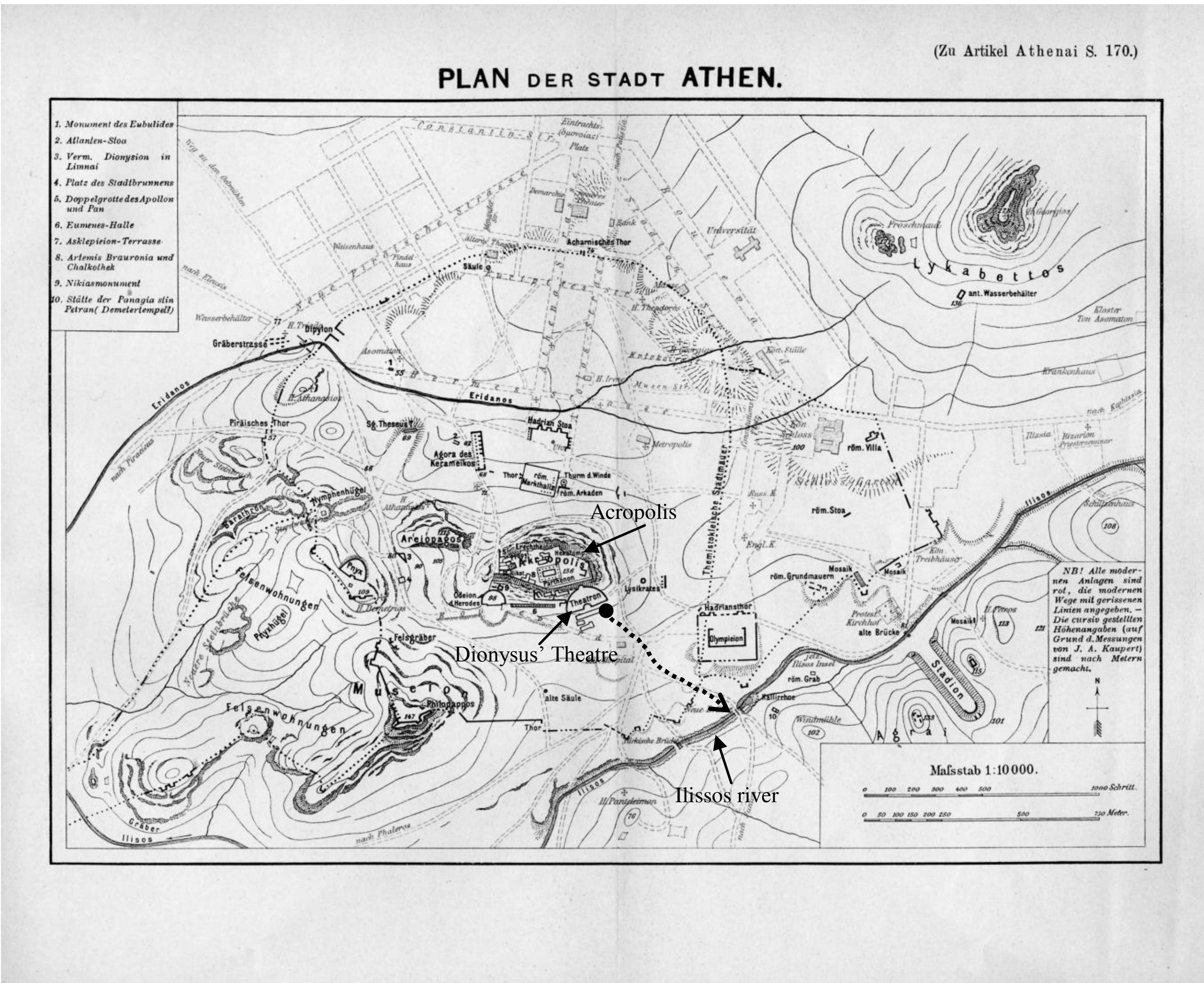


Figure 12. Possible wastewater and rainwater course (dotted line) to the Ilissos river (arranged by K. Kollyropoulos on a base drawing of Curtius & Kaupert, 1878)

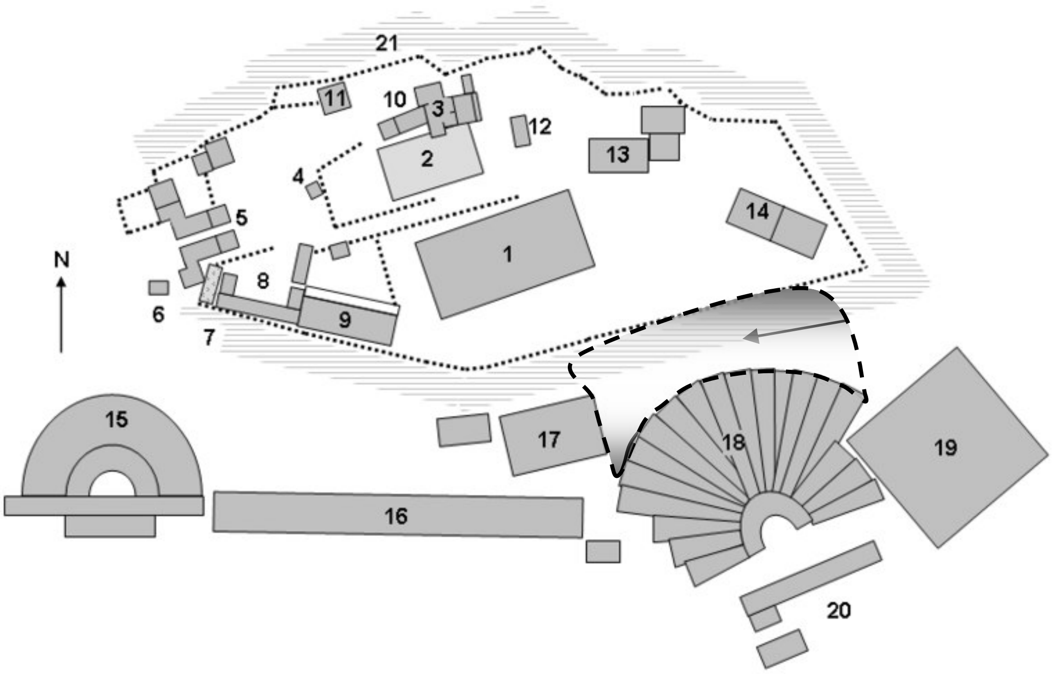


Figure 13. The draining areas A.1 & A.2 (in the site plan of the Acropolis) (plan of Madmedea, arranged by K. Kollyropoulos)

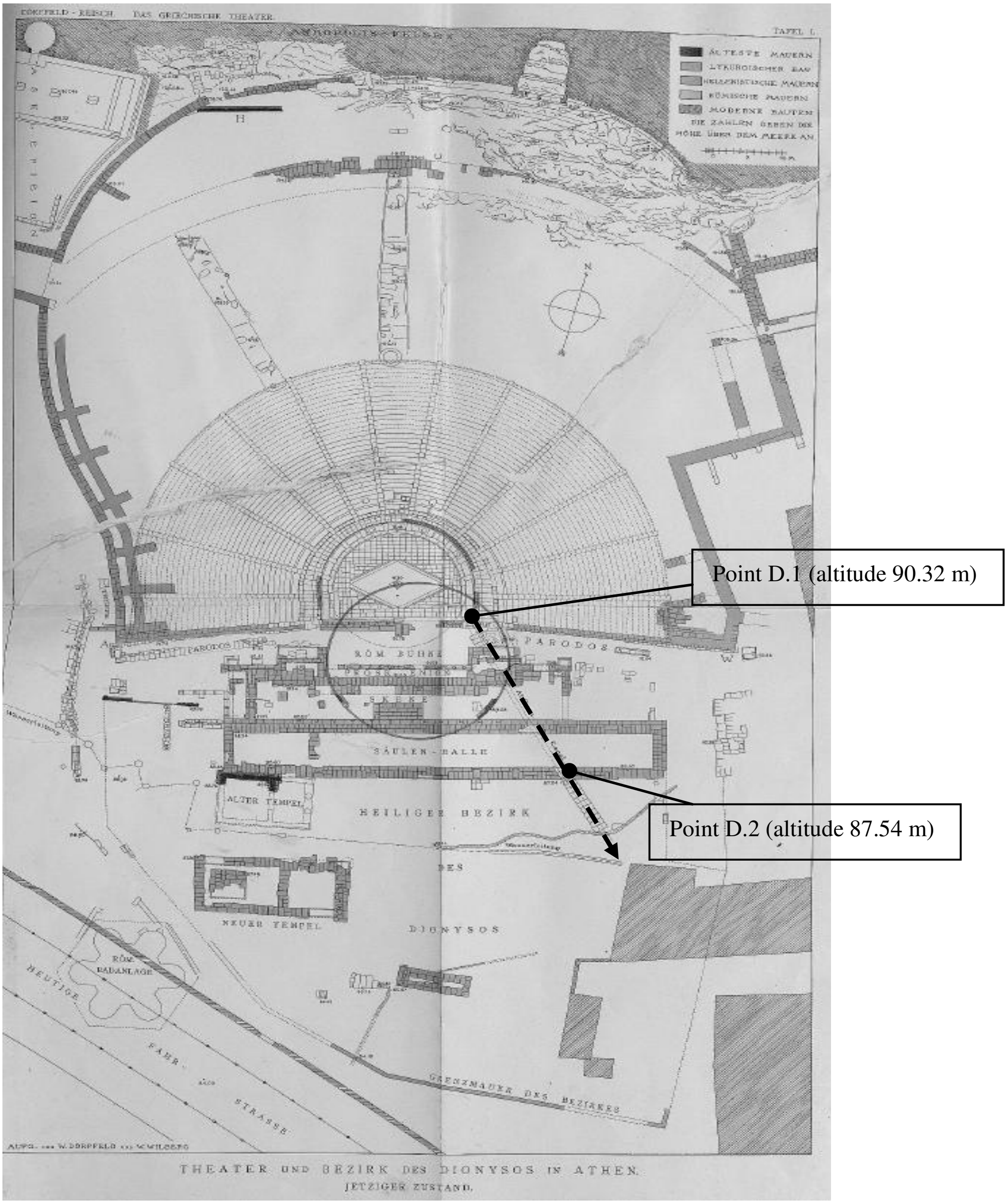


Figure 14. Graphical calculation of critical path (dashed line D.1-D.2) of drainage channel (arranged K. Kollyropoulos on a base drawing of Dörpfeld 1896)