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Review

The Historical Development of Sewers Worldwide

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Abstract: Although there is evidence of surface-based storm drainage systems in early Babylonian and Mesopotamian Empires in Iraq (*ca*. 4000–2500 BC), it is not until after *ca*. 3000 BC that we find evidence of the well organized and operated sewer and drainage systems of the Minoans and Harappans in Crete and the Indus valley, respectively. The Minoans and Indus valley civilizations originally, and the Hellenes and Romans thereafter, are considered pioneers in developing basic sewerage and drainage technologies, with

emphasis on sanitation in the urban environment. The Hellenes and Romans further developed these techniques and greatly increased the scale of these systems. Although other ancient civilizations also contributed, notably some of the Chinese dynasties, very little progress was made during the Dark ages from *ca*. 300 AD through to the middle of the 18th century. It was only from 1850 onwards that that modern sewerage was "reborn", but many of the principles grasped by the ancients are still in use today. This paper traces the development of the sewer from those earliest of civilizations through to the present day and beyond. A 6000 year technological history is a powerful validation of the vital contribution of sewers to human history.

Keywords: bathrooms; Bronze Ages; Byzantine world; Etruscan civilization; Indus valley civilization; Knossos; Lavatories; Roman Empire; Ottoman; Sanitation

1. Introduction

Drains in the streets are known since the early Mesopotamian Empire in Iraq (*ca*. 4000–2500 BC). However, well organized and operated sewerage and drainage systems were practiced for the first time in the history of humankind by the Minoan and Harappan civilizations in Crete, and in the greater Indus valley, respectively after *ca.* 3000 BC [1]. It is evident that during the Minoan era extensive drainage systems and elaborate structures were planned, designed and built to protect the growing population centers and the agricultural land. In several Minoan palaces discovered by archaeologists in the 20th century, one of the most important elements was the provision and distribution of water and the transfer of stormwater and sewage in drains by means of hydraulic systems [2]. Minoans and Indus valley civilizations, originally, and Hellenes and Romans thereafter, are considered pioneers in developing the basic hydraulics of sewerage and drainage systems technologies, with emphasis on sanitation in the urban environment. Hellenes and Romans further developed these technologies and greatly increased the scale of their provision [3].

Very little progress was made from *ca.* 300 AD (during the so called Dark Ages) through to the middle of the 18th century. From 1850 the "state-of-the-art" for sewage disposal had advanced considerably further than that for sewage collection and conveyance. Cities and towns had the benefit of knowing the actual connection between sewage and the sources of drinking water (e.g., the adverse potential impact on their health/welfare). That knowledge resulted in great strides being made in collecting and conveying sewage from/away from people's homes, and in treating the sewage prior to its discharge either into their source of potable water or at a point near their source [1].

In this study, a timeline of historical development of sewerage and drainage systems worldwide over the last 5500 years of the human history is considered and discussed. Characteristic paradigms of the major civilizations, such as Minoan, Egyptian, Harappan, Chinese dynasties, Hellenistic, Roman, Byzantine, Venetian, Ottoman, and modern time drainage and sewerage sewers and drains are referred to which justify the significance of that technology with respect to world history. A chronological order is followed where possible and convenient for the aim of the study. Rapid technological progress in the 20th century created a disregard for past water technologies that were considered to be far

behind the present ones. Even so, there are still a great number of unresolved problems related to sanitation principles and of course to sewerage and drainage systems. In the developing world, such problems have been intensified to an unprecedented degree.

Although a great deal of research and literature with emphasis on the historical development of hydraulic infrastructure in ancient civilizations are known, there is a lack of corresponding information on wastewater management, and especially on sewerage and drainage systems in ancient civilizations. This is somewhat surprising since the lack of sanitation affects human development to the same or an even greater extent as the lack of clean water [2]. Hence, this paper aims to trace the development of sewerage and drainage technologies of the ancient civilizations and to examine their influence through the centuries to more recent times and beyond.

2. The Early Civilizations

2.1. Eshnunna/Babylonia and Mesopotamian Empire in Iraq (ca. 4000–2500 BC)

The Mesopotamian Empire states of Assyria and Babylonia marked great advances in civilization during the 2nd millennium BC. The ruins of Mesopotamian cities contain well-constructed storm drainage and sanitary sewer systems. For example, the ancient cities of Ur and Babylon, located in present-day Iraq, had effective drainage systems for stormwater control [4]. The systems contained vaulted sewers and drains for household waste, and gutters and drains specifically for surface runoff [5]. The material of choice was baked brick with an asphalt sealant. Rainwater was also collected for household and irrigation uses. The Babylonians were partially motivated to construct urban drainage systems by their desire to remain clean. The Babylonians, like other ancient civilizations, viewed uncleanness as a taboo, not because of the physical uncleanness but the moral evil it suggested [6]. In retrospect, the Mesopotamians viewed urban runoff as a nuisance flooding concern, waste conveyor, and a vital natural resource.

In Babylon, in some of the larger homes, people squatted over an opening in the floor of a small interior room. The wastes fell through the opening into a perforated cesspool located under the house. Those cesspools were often made of baked perforated clay rings, ranging in size from 45 to 70 cm in diameter, stacked atop each other. Smaller homes often had smaller cesspools (45 cm diameter); larger homes had larger diameter cesspools [7].

The origin of the earliest known pipe in Babylonia was documented by many as one of the first places to mold clay into pipe (via potter's wheel). Tees and angle joints were produced and then baked to make drainage pipe, as early as 4000 BC [8]. Stormwater drain systems in some streets were constructed of sun-dried bricks or cut stones. Some homes were connected to these drains.

2.2. In Scotland (ca. 3200 BC)

In Scotland, in the village of Skerrabra or Skara Brae as it has become known, excavations showing early drainage systems are located. Radiocarbon dating in the early 1970s confirmed that the settlement dated from the late Neolithic-inhabited for around 600 years, between *ca.* 3200 and 2200 BC [9]. A remarkably sophisticated drainage system was incorporated into the village's design-which may

have included an early form of toilet facilities [10]. The complex drainage system seems to serve both roof drainage and the removal of liquid waste from certain buildings [11].

Mackie [12] defined "extremely evocative" the two visible sections of the main drain that he had the opportunity to see. He described the drain as a substantial, dry-walled channel, far down below the hut floors and roofed with massive lintels. In the opinion of Mackie [12], "this was a planned settlement, the drain of which was presumably built first, no doubt connecting with smaller drains from some of the huts to give an extraordinarily hygienic quality to the settlement. There was nothing like this drainage system in Scotland again until the Romans arrived."

3. Bronze Ages

3.1. Minoan Civilization (ca. 3200–1100 BC)

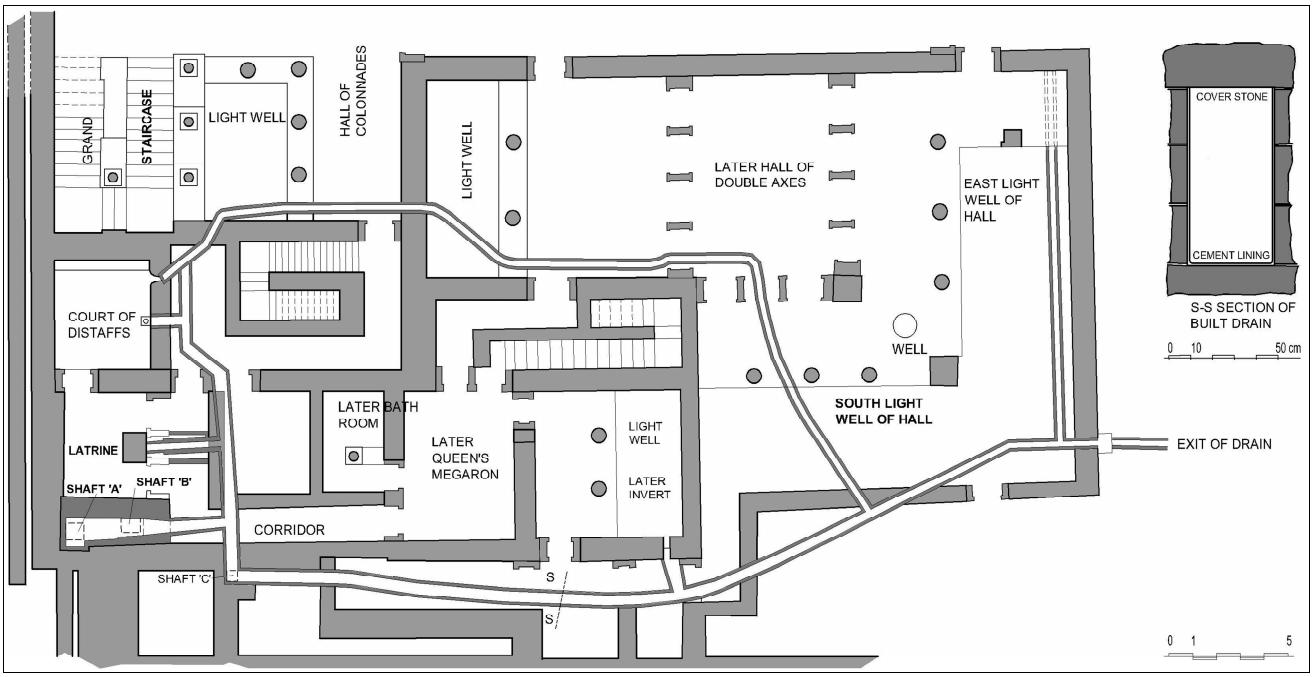
The island of Crete in Hellas, was first inhabited shortly after *ca*. 6000 BC but it was only during the Bronze Age that the Minoan civilization (*ca.* 3200–1100) was developed as the primary Hellenic cultural center of the Aegean world [13]. The Minoan and Mycenaean settlements (in Crete and Peloponnesus, respectively) developed and applied various technologies for collecting and disposal of stormwater and sewage [13]. From the early Minoan period (*ca*. 3200–2300 BC) issues related to sanitary techniques were considered of great importance and developed accordingly. Archaeological and other evidence indicate that during the Bronze Age advanced wastewater and stormwater management were practiced. Several types of stone and terracotta conduits and pipes were used to transfer water, and drain stormwater and wastewater. These types of conduits are summarized by Angelakis *et al.* [13].

Minoan plumbing and drainage were well developed. In several Minoan palaces discovered by archaeologists in the 20th century, one of the most important elements was the provision and distribution of water and the removal of waste and stormwater by means of sophisticated hydraulic works. The sewage and drainage systems are mainly stone structures. Stone conduits formed drains which led rainwater from the courts outside the palaces, to eliminate the risk of flooding [1].

In addition, sewerage and drainage systems were formed of terracotta pipe (clay pipe with bell and spigot joints, sealed with cement) and lithic open-topped channelized drains conveyed storm water primarily, but also human wastes. Some of the sewers were large enough for people to walk through [14]. Many of the drains from *ca.* 2000 BC are still in beneficial service today on Crete. Integrated sewerage and drainage systems were implemented in palaces (e.g., Knossos, Phaistos, and Zakros). However, some toilets were flushed with water from large jars. The first known "flushed" toilet was implemented at the Knossos palace. The toilet consisted of a wooden seat, earthenware "pan" and the rooftop reservoir as a source of water [1]. The toilet was connected to the central sewerage and drainage system at Knossos palace. Bathtubs with no sewers were also used. The sewerage and drainage system in the palace of Knossos beneath the Domestic Quarter is shown in Figure 1.

The complicated drainage and sewerage systems of Minoan palaces were greatly admired by people from other areas and/or from later periods, while sometimes they were also misunderstood. It can be argued that this is one of the factors that led to the conception of the complicated labyrinth mentioned in the Hellenic myth of Theseus and the Minotaur [15].

Figure 1. Part of the sewerage and drainage system in the palace of Knossos [3] (with permission of George Antoniou).



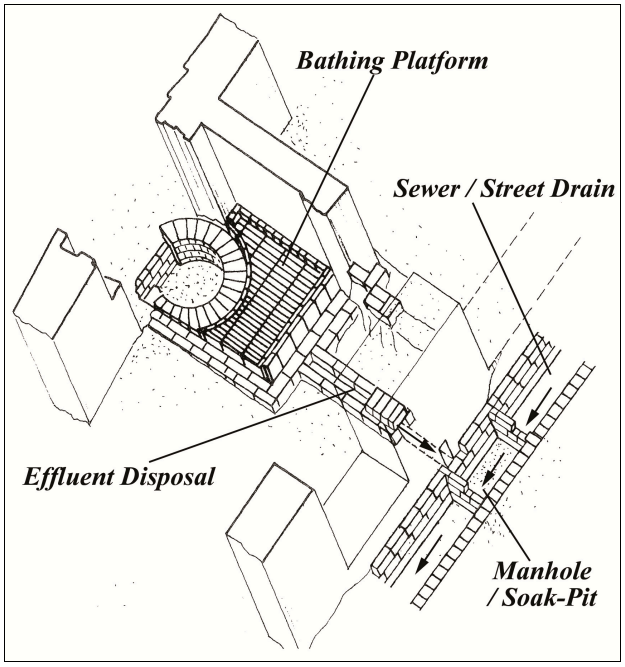
3.2. Harappan Civilization (ca. 3200–1900 BC)

The Indus or Harappan civilization was a Bronze Age culture (*ca*. 3200–1300 BC with a Mature Period of *ca*. 2600–1900 BC) developed in the north-western region of the South Asian subcontinent. This civilization developed commerce, wheeled vehicles, irrigated agriculture, domesticated animals, cotton and silk textile proto-industries [16]. The Harappan civilization is the most ancient South Asian culture having implemented a complex and centralized wastewater management system. Indeed, one of the major characteristics of this culture is to have developed lavatories, and drainage and sewerage systems [17–19]. It was during the Mature Harappan period (or Urban Harappan Phase) that centralized sanitation with sewers first appeared. The most representative places of the Harappan culture of that very period are the sites of Harappa, Mohenjo-Daro and Lothal [2]. Similarly to the Minoans, the Harappans have developed advanced sewerage and drainage systems. Wastewater management of the Harappan sites was of two types: one centralized, with sewage and drainage networks, the other decentralized, with soak-pits and/or pierced jars [20]. But, in the sites where centralized wastewater management was implemented, as in Harappa, Mohenjo-Daro and Lothal, decentralized techniques were also used for the houses isolated from the existing sewage network [21].

The sewage system of these three sites was made of standardized baked-bricks set in clay mortar. Drains were covered with stone, wooden boards, or baked-bricks, and in Mohenjo-Daro and Harappa sometime assembled in corbelled vault [17,21]. Liquids entered brick-lined pits, having manhole function (control and cleansing) as well as sedimentation pits [22]. Then the effluent flowed into a larger drain [17]. Figure 2 shows an example of this approach. Bathrooms and lavatories were often located next to each other on the street side of the building, and wells were often in an adjacent room. Only a few houses had lavatory in Mohenjo-Daro [23] (p. 122), and it is considered that in Lothal a single house was equipped with that facility [24] (p. 81). Also water was used in lavatories for flushing [1].

Second-floor bathrooms existed, with terra-cotta piping and vents. Thus, the sewage system was a network of drains made of baked-brick running along the streets. The drains were located along one side of the street and were U-shaped with a depth of approximately 50–60 cm. In some buildings, effluent flowed into the public drain or into a catchment basin by means of wall drain chutes [25,26].

Figure 2. Scheme of domestic wastewater disposal of an urban agglomeration of the Harappan civilization (inspired by [17]).



The Harappan civilization developed a well-organized sewage network in a few urban agglomerations. While Harappa and Mohenjo-Daro covered about the same surface (around 100 ha during the Mature Harappan Period), Lothal was much smaller (around 25 ha) [27]. Interestingly, Dholavira, which was a large city of about 100 ha as well, did not have a centralized sewage network at all: wastewater disposal was only about soak-pits and pierced jars, whereas it has been demonstrated that this very site had stormwater drains [28] (p. 32). Conversely, the site of Chanhu-Daro covered an area of only 6 ha [29], but had a centralized sewage system with drains [30] (p. 531). Thus, it seems that Harappan centralized sewage system did not depend on the surface extent of the town, but most probably on socio-political factors.

4. Ancient Egyptians (*ca.* 2000–500 BC)

The Early Dynastic Period is a period of some 5000 years or more, the beginning of which is conventionally considered as the history of Ancient Egypt. A very important change that marks this period is the rise of urbanism. Inhabitants of small settlements throughout the country abandoned their homes and moved to larger communities and cities. In the elite and religious quarters of the Egyptian city of Herakopolis (BC 2100), there was a deliberate effort made to remove all wastes, organic and inorganic to locations outside the living and/or communal areas, which usually meant the rivers. Finer houses had bathrooms and toilet seats made of limestone. The bathroom would be fitted with a slightly

inclined stone-slab floor and the walls were typically lined to a certain height (about half a meter) with battered stone slabs to protect against dampness and splashing [31]. Drainage of wastewater was provided by setting a basin beneath the spout of the floor slab in the bathroom, or sometimes by drainage channels running through the outer wall into a vessel or straight into the desert sand. Certain homes of aristocrats had copper pipes that carried hot and cold water. The less wealthy who could not afford to have a limestone toilet, used toilet stools, under which a ceramic bowl was placed. Furthermore, toilet stools with a hole in the middle and a clay pot beneath were also used as portable toilets and they were often buried with senior officials [31]. The excrement, which was collected in jars containing sand, was emptied into pits outside the walls of the house, in the river and even in the streets. Instead, poor people used wooden stool with a hole on it. The toilets used beds of sand to catch/contain the wastes. Servants cleaned the sand regularly [32].

At the same time, ancient Egyptians were early developers of pipes. In the beginning, of course, their pipes and fittings were very crude. Like the Mesopotamians, they used clay pipe made from a combination of straw and clay. First it was dried in the sun, and then baked in ovens. As they improved, they worked deposits of the lead ore galena at Gebel Rosas to make net sinkers and plumb bobs. They were also early developers of Copper and the techniques of making copper alloys. Copper was the most important metal for tool making in ancient Egypt and was smelted in furnaces from malachite ore mined in the Sinai [33].

Copper pipes were used to build elaborate bathrooms inside the pyramids and intricate irrigation and sewages systems (2500 BC). According to their religion, to die was simply to pass from one state of life to another. If the living required food, clothing and other requirements of daily life, so did the dead. Thus, it's not surprising that archaeologists have discovered bathrooms in some tombs.

Excavators of the mortuary temple of King Suhura at Abusir discovered niches in the walls and remnants of stone basins. These were furnished with metal fittings for use as lavatories. The outlet of the basin is closed with a lead stopper attached to a chain and a bronze ring. The basin emptied through a copper pipe to a trough below. The pipe was made of 2.5/40 cm beaten copper to a diameter of a little less than 5 cm. A lap joint seam hammered it tight. Also, found within a pyramid temple built by King Tutankhamen's father-in-law at Abusir, was a brass drain pipe running from the upper temple along the connecting masonry causeway to the outer temple on the river.

Excavators have discovered a tomb which supposedly contains the body of Osiris before he became a god. It contains the dividing line between Life and Death, *i.e.*, a deep moat containing water that surrounds all sides of the figure of the god on his throne. After 5,000 years, water still fills the canal through underground pipes from the River Nile. Recent excavations made on the site of Solimans Temple, establishes the fact that a thorough system of drainage and sewerage, was provided for the temple and its surroundings [34].

5. China

Archaeological evidence shows that the history of the sewer in China dates back more than 4000 years. At this time, some cities were formed in the mid reach of the Yellow River, and this brought the need for urban drainage including wastewater from the residential areas, especially in the royal palaces.

The earliest sewer facility was discovered in the old town Pingliangtai of Henan province. Remarkably, earthenware was used to build the sewer inside the town, including some earthen pipelines for drainage under the street (Figure 3) [35]. In the period 10th–15th century BC, in the Shan dynasty, many towns were formed near the Yellow River basin, and at same time urban drainage improved accordingly. Archaeological discovery from Xihaocheng, today's Yanshi city of Henan province, has shown that a systematic drainage system had been built inside the 190 ha town. There was an underground urban drainage raceway of 800 m length from the East Gate to the palace. Inside the palace, there were branch sewers for draining of rainwater and wastewater. The underground raceway was 1.3 m in breadth and 1.4 m in height, and led water from the palace and town into the moat [36].

In 1100–221 BC, there were many kingdoms in the center of China close to the Yellow River basin and the Yangtse River lower basin. Archeological discovery shows that urban drainage had been developed to a high level in Lingzi town, the capital of Qin kingdom in today's Zibo city of Shandong Province. At that time, Lingzi covered an area of 15 km^2 with 300,000 inhabitants. A complex water supply and drainage system was built combined with river, drainage raceway, pipeline and moat. The town was built close to the river, so the river had become the water supply resource that linked with the moat which surrounded the town walls by a canal and later crossed the town wall into the town to connect with the urban water system. Inside the town, three raceway networks were built that linked with the supply canal to deliver the water from the river for daily use and gathered wastewater and stormwater on the way. Finally, a canal introduced the water across the town wall again into a moat and flowed into the lower reach of the river [37]. Archaeological excavations also uncovered a large drainage station under the west town wall. The structure was made of stone, 43 m in length and 7 m in breadth. It led water from the town and passed the bottom of the town wall into the river. The aqueduct had 15 outfalls that distributed in three stories, 5 outfalls per story. The drainage system of Lingzi town is the oldest and the biggest in ancient China discovered to date [38].

Figure 3. The earthen pipeline before 4000 years (with permission of Xiao Yun Zheng).

In 221 BC, the Qin Empire, the first united country in Chinese history, was founded in today's central China. Qin Shi Huang. According to historical documents, the capital Xianyang, in today's Shanxi province, although long disappeared was large for the time. Recent discoveries have indicated that drainage facilities were built in the town using earthenware pipes. For example, an archaeological

dig in the palace ruins found a drainage facility combined with 4 pools and sewers. It gathered the palace rainwater and wastewater by sewers and raceways (uncovered) to the pools, and used a pipeline to lead water into the river. In 2006, a large sewer system was discovered in the old Qin Palace Efanggong, the countryside of today's Xi'an city, consisting of groups of three pipes. Sewerage existed not just in the palaces but also in residential areas. Earthenware sewers were discovered at the Shanjailing ruin of Shanxi Province, including a rare elbowed pipe.

The Han Dynasty (202–220 AD) brought with it major advances in urban development. According to historical documents, its capital Chang'an, near today's Xi'an town of Shaanxi province, quickly grew to be a large town and survived as the capital for 15 dynasties until 907 AD. Chang'an town covered 35 km^2 with a population of 500,000 inhabitants [39]. Archaeological discoveries have shown that a complex water system including drainage was built in the town that combined with functions of water supply, drainage, storage and ship transportation. A sewer system was built combined with ditches and sewers. The ditches were mainly built along with the main streets of the town, but linked with underground sewers from the residential areas and palaces. The sewer pipelines were mainly built with earthenware but some major sewers were built with bricks. It was a remarkable achievement to build sewers with brick in this age making it possible to build them longer, bigger and stronger. This technology continued during the next thousand years. For example, excavations in the 1970s found that there were brick sewers along the main streets and earthen pipes in many places in the town [40]. In 2008, a major brick sewer was found in the old Chang'an town. This sewer was 2 m in width, and until now 40 m of length has been discovered.

Chang'an was not just a flourishing town but also a very important stage in the history of urban construction of China because the form of urban water system there influenced design and construction greatly in the following dynasties [41]. The ancient sewer system included four parts: (1) small sewers from the house; (2) residential sewers linked with the house sewers; (3) main sewers along the streets linked with the residential sewers; (4) drainage ditches and the rivers receiving water from the sewers.

Other examples of ancient Chinese sewers have been excavated. An old sewer dated from the Tang dynasty (618–907 AD) was discovered in Yangzhuo town. According to the report [42], the sewer measured 35 m in length, and 1.75 m in width and 1.5 m in height. Moreover, another main underground sewer for rainwater was discovered in Yangzhuo town. It is a brick and wooden structure, 1.8 m in width and 2.2 m in height, with 12 m of sewer opened by excavation so far.

After the Song dynasty (960–1206 AD), sewers were usually built of brick or stone blocks, or consisted of a structure made of bricks and stones. The walls of the sewer were built of bricks and covered by a flagstone. From this period, two types of sewer construction were popular. One was the raceway built underground to introduce wastewater or rainwater. That type of sewer was usually built of brick with a dome. The other type was built along the street, usually constructed along the two sides of the street or inside the street. The walls were built of brick and covered with flagstones. It was still very common in many cities until to the 1950s. Even today, the under-street sewer still exists in the old town of Huai'an (Figures 4 and 5), as in some other small towns. Finally, the wastewater and rainwater were channeled into the town's river, following the sewer structures of the ancient Chinese towns.

Figure 4. The sewer under the street (with permission of Xiao Yun Zheng).

Figure 5. The street with the sewer system (with permission of Xiao Yun Zheng).

6. Historical Times

6.1. Etruscans (ca. 800–100 BC)

The Etruscan civilization flourished in Etruria, the region on the western side of central Italy delimited on the north by the river Arno and on the south by the river Tiber. The Hellenes profoundly affected the Etruscans, and then they in turn had an intense effect on the early republic of Rome [43].

Usually, Etruscans towns had drainage channels on the sides of streets, such as the case of the ancient town of Marzabotto, located in Northern Italy, in the Po Valley [2,44]. The system was based both on the natural slope of the plateau and on an artificial modification. The system was planned in order to avoid water runoff interacting with the two necropolis located between the urban area and the river Reno, where wastewater was usually discharged [2].

Forcello, in the province of Mantova, in the Lombardy region, is another example. The drainage and discharge systems were based on two drains with the main function of the town sewer and arguably assuring the drainage of the area occupied by the houses [2,45]. It has to be highlighted that in the more ancient Etruscan towns the drainage network was not as ordered and regular as in the cases just mentioned. Such an ordered urban drainage network was present only in the late settlements outside of Etruria *strictu sensu*, in areas which can be considered Etruscan colonies, built *ex novo* following a rational plan, as in the case of Marzabotto and Forcello [2].

The town of Perugia, in Umbria, is rich with *cuniculus*, which are drainage tunnels mostly dug into the natural conglomerate. The tunnels of Perugia assured effective drainage [46], because they were always placed in correspondence of contact between conglomeratic and silt-sandy soils or within the thickness of the filling soil [2].

6.2. The Classical and Hellenistic Periods (ca. 480–67 BC)

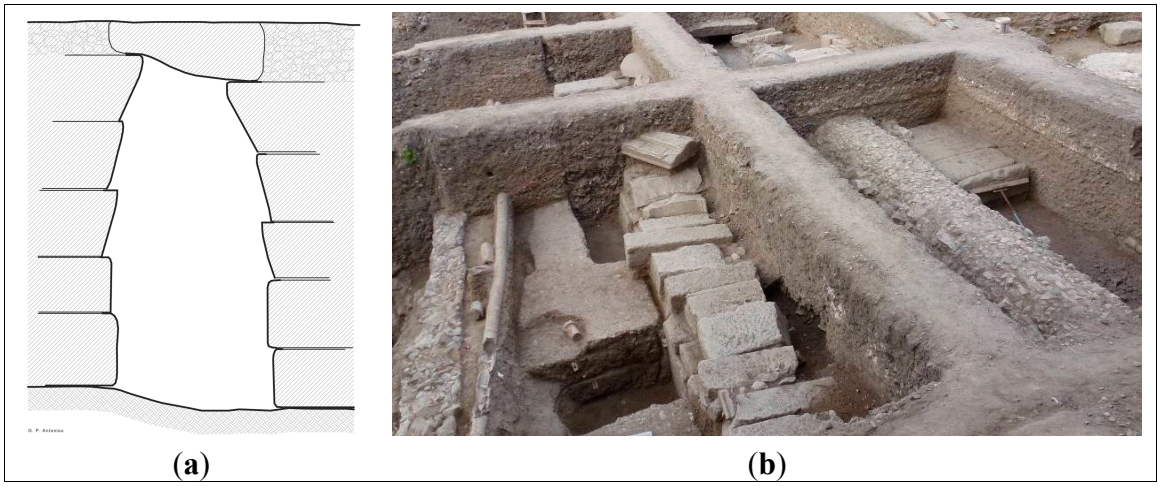
In ancient Hellas, the realization of the importance of water sanitation is evident already from the early Archaic period. Later, Alcmaeon of Croton (floruit *ca*. 470 BC) was the first Hellene doctor to state that the quality of water may influence the health of people. Also, Hippocratic treatise *Airs, Waters, Places* (*ca.* 400 BC) deals with the different sources, qualities and health effects of water [47]. Thus, the importance of water for the public health for first time was recognized and the first well organized baths, toilets, and sewerage and drainage systems appeared [48].

Several pipe networks supplied water to all kinds of settlements and sanctuaries as well. Ceramic and stone built conduits were the regular material of the networks of that era. Also pipes of lead (of length of 3 m or more) and bronze were used by the Hellenes to distribute water, usually during the late Hellenistic period, rarely as pressure pipelines too [49]. In the aqueducts of that era a few above-ground structural arches were incorporated and many tunnels through hills, siphons under valley and rivers, and other structures were also implemented [50].

Along with the water supply networks, extensive sewerage systems evolved not only within the urban network but also incorporated into individual residences and building complexes. During the pre-Classical and early Classical times the sanitation in most towns, including Athens, *was certainly very primitive* [51] despite the archaeologically testified existence of drains and kind of sewers. Later on, and especially at the late Classical and Hellenistic era, sanitary installations became a necessary space even for ordinary middle class houses (e.g., Olynthos, Delos, and Dystos).

The well documented sewerage in ancient Athens [49,51] presents not only the *ca*. 5th century BC original Great Drain—which was up to 2.40 m deep—and its branches, but also the enrichment of that system in the *ca*. 4th century BC. Parts of sewers and drains in Hellenistic Agoras (Athens and Kos) are shown in Figure 6.

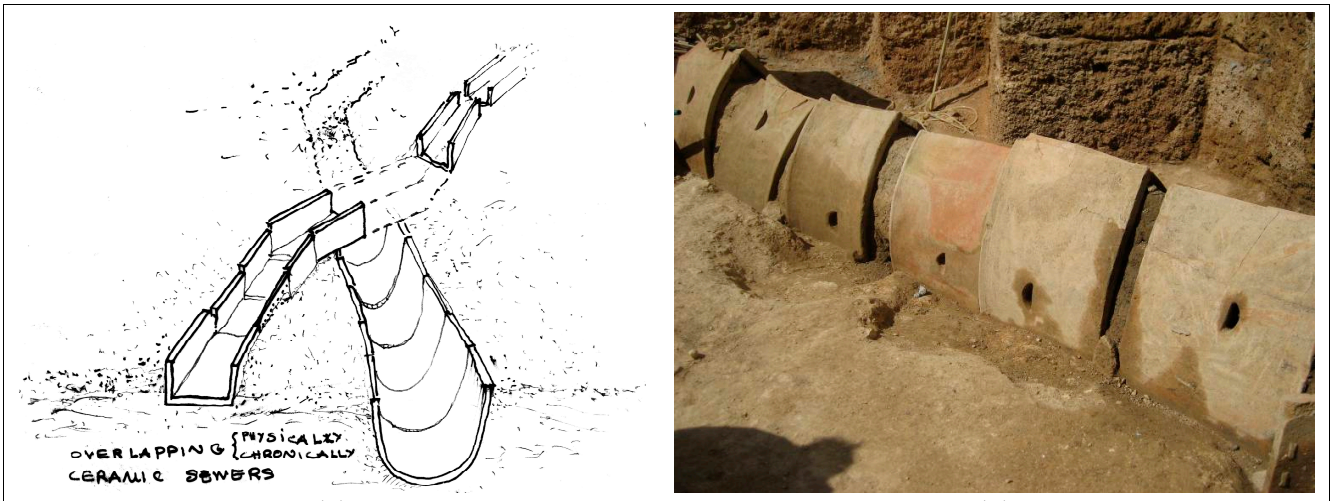
Figure 6. Parts of sewers and drains in Hellenistic Agoras: (**a**) Cross section of a bridged sector of the Great Drain in Athens G. Antoniou, inspired by [51] and (**b**) Various types of sewers and their repairs in Kos (with permission of George Antoniou).



(**a**) (**b**)

The sewers in Athens delivered storm water, human wastes and generally effluents, to a collection basin outside the town, implementing for that also the Eridanos River. From that basin, the storm water and wastes were conveyed through brick-lined conduits to fields to irrigate and fertilize fruit orchards and field crops. Possibly, the historically known epidemic of *ca*. 430–426 BC in Athens, [7] contributed to the enhancement of the sewerage system of the town during the *ca.* 4th century Holes were left in the walls of the drain channel (main sector and/or branches) as inlets for the effluents of the adjacent houses. These house drains too were constructed in various ways; one for example had carefully built stone walls and was covered with tiles and flat slabs; others were simply made of inverted roof tiles [51]. Several manholes at the covered sectors of that network reveal the provision for cleaning and maintenance. Remains of sewers and drains in Hellenistic Athens are shown in Figure 7.

Figure 7. Remains of sewers and drains in Hellenistic Athens: (**a**) Drains south of the Middle Stoa (Sketch by G. Antoniou) and (**b**) Duct covered with prefabricated ceramic well ring sectors in south foothills of Acropolis.



(**a**) (**b**)

Despite the central drains or sewers, many streets had conduits running centrally or alongside them [3]. Sewers of that kind have been discovered in many ancient Hellene towns as in Delos [52], in Olynthos [53,54], in Lefkas, Kassope, Priene [55], Dion, Minoa in Amorgos and many more! As far as concerns the construction of these sewers and drains, they were mostly stone built covered usually with stone slabs or less frequently with ceramic pieces as in Eleusis [56]. Despite that there were ducts cut in stone blocks as in Athens [51] and conduits cut in the natural rock itself. Moreover the existence of ceramic round and U or inverted Π shaped pipes was not rare for public spaces as roads. These kinds of conduits were found more often inside the houses as in Delos and in Olynthus. Except the well or impromptu covered subterranean or semi-subterranean ducts there were also uncovered ones by the side edge of the streets as in Delos [52] or shallow ones at the center, as in Kassope [55]. In cases of two story buildings vertical ducts incorporated in the walls have been found, as those in Delos [52,57]. Possibly they were conveying the rainwater to the relevant residential cisterns. Sewers along the streets and inside the mansion of the Masks in the island Delos are shown in Figure 8. Also sections of sewers and drains in the ancient Delos are shown in Figure 9.

Figure 8. Sewers along the streets and inside the mansion of the Masks in the island Delos [58].

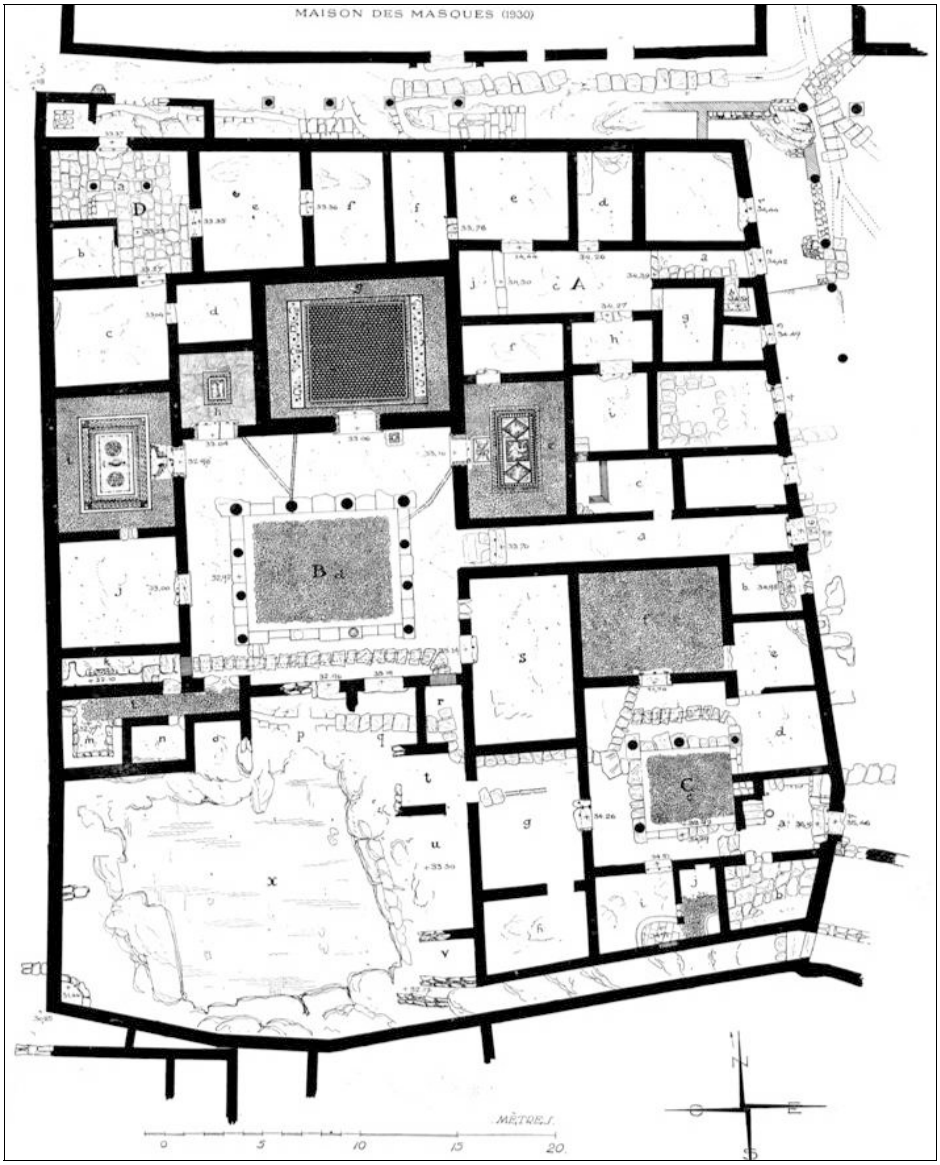
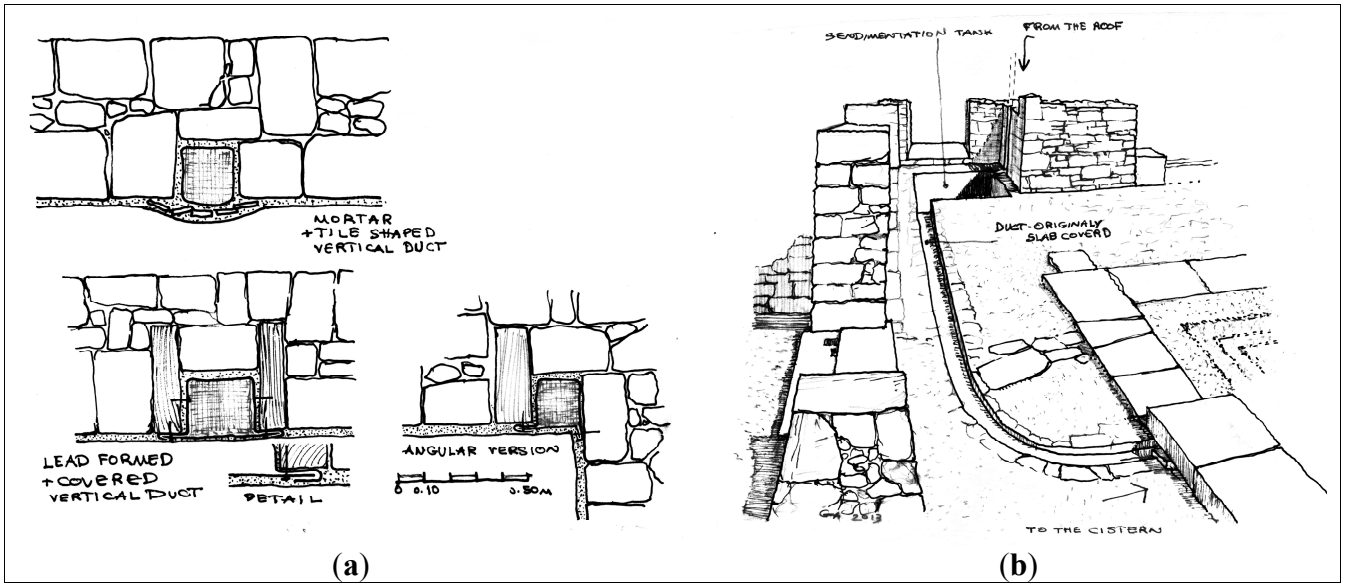


Figure 9. Sewers and drains in the ancient Delos: (**a**) Types (A, B, and C) of vertical ducts and (**b**) Sedimentation basin in Diadumene mansion leading rainwater to the cistern. G. Antoniou inspired by [57].



Generally most of the late Classical and Hellenistic towns designed according to the, so called, Hippodamian layout had their town blocks—*insulae*—separated also by a sewer [55], even the smaller ones as Lefkas, Kassope, *etc.* On the other hand even during the *ca*. 4th century BC there were few well planned towns without sewers under or by their street paving, as Orraon [55].

After the late Classical period many houses were equipped with their own domestic sewers network which was consisted by slab covered ducts or/and ceramic pipes, usually under the pavement. That network put out from bath and/or inner yards the wastewater and/or the rainwater. Occasionally communal subterranean sewers crossed private residences in order to ensure optimal management of the *enffluentia* (*i.e.*, the sewage effluent) of the community [55], often under specific regulations.

Special features had been constructed to ensure the proper outfall of wastewater through the fortification walls as in Amphipolis and Minoa in Amorgos Island (Figure 10a,b). They were twin, triple, *etc.* openings at the walls usually as narrow to prevent the entrance of intruders.

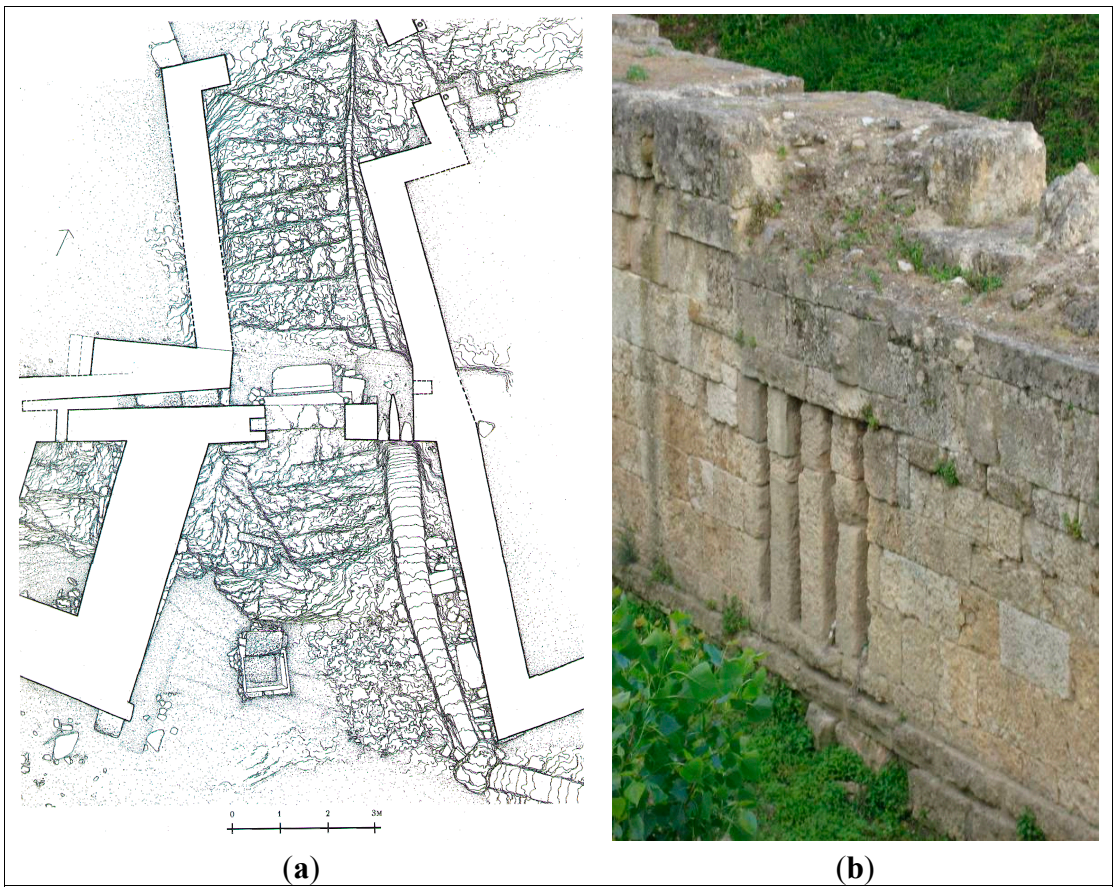
The sewers network was commonly gathering wastewater, rainwater and generally all the *enffluentia* of the settlement. In several cases it was laid out in a way providing significant grade of reuse [59]. On the other hand there are some exceptions where there was separate wastewater network and independent rainwater drainage system [60].

The Sewers of the Ancient Theatres

A quite significant feature of the sewers during the Hellenic antiquity is the sewer system for the drainage of ancient theatres. The problem of the rainwater management of the spacious open areas of the ancient Hellenic theatres is an aspect which was incorporated into their design since the earliest years of their appearance, due to the nature of these unroofed constructions. Their shape functioned as a typical runoff surface and therefore the necessity for the drainage of the rainwater was essential. Due to that importance and necessity, the drainage of the theatres built in stone was constructed at the

beginning. Cases where the drain conduits were added later [61], seem to refer mostly to originally wooden constructions, as the Dionysus theatre in Athens, which was rebuilt or reformed into stone constructions.

Figure 10. Features of Hellenic sewers: (**a**) Slab covered duct cut in the rock and twin outlet opening in the main gate of sewer in Minoa Amorgos and (**b**) Quadruple sewerage opening at the fortifications of Amphipolis (with permission of George Antoniou).

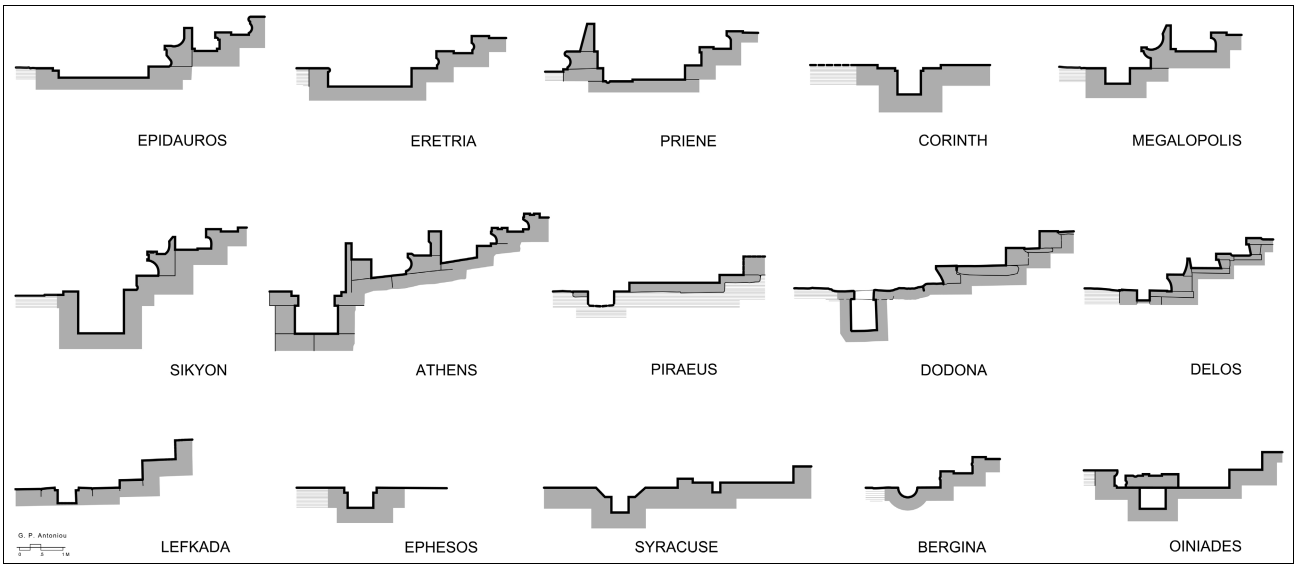


(**a**) (**b**)

The drainage system used existing parts of the construction as the stairs and the corridors to lead the rainwater to the lower surface of the theatre, the circular *orchestra*. From that part an articulated sewage system took the water quantities off. The main semicircular sewer which was situated at the edge of the *orchestra* was called *Euripos* [62] or *Ochetos*. It was an originally uncovered duct which had at the earlier examples covering stone blocks only at the spots corresponding to the stairs. The layout and the formation of that duct presented several variations [63]. Later on it was covered with slabs and the rainwater was drained to the duct through waterspouts of various forms, as in the theatres of Dionysus in Athens, Epidaurus in Peloponnese, Ephesus in Anatolia, Philippoi in Makedonia, *etc.* Cross sections of several types of main drains of ancient Hellenic theatres are shown in Figure 11.

Referring to the outward path of that drainage channel, a variety of formations have been testified. Usually it ended to the one of the two sides of the *orchestra* and through an underground conduit under the side corridors—*Parodoi* and/or the scene building—piped the water away of the theatre. Quite often the rainwater was drained out through *Parodoi* and less often through a central duct under the middle of the scene building.

Figure 11. Cross sections of several types of drain ducts of ancient Hellenic theatres. G. Antoniou, inspired also by [63].



The terminal basin of the drain was varying according to the position of the theatre. A nearby creak or torrent was the most usual case—as in Epidaurus—when the theatre was outside or at the edge of the town or sanctuary. Existing karstic crevasses was a convenient but rare case as in Dodona. Also seems that that drainage provided in some cases the reuse of the water via a duct passing through a workshop area. Finally in places with water shortage, as Delos, a cistern was the final collector [64].

That typical ancient Hellenic feature was incorporated also in the theatres of the Roman era. That period it was formed in a tidier manner, usually being totally covered with regularly small waterspouts.

6.3. The Roman Period (ca. 750 BC–330 AD)

The Romans are usually cited for the magnificence of their aqueducts in terms of hydraulic infrastructure, but they also gave an extraordinary contribution to the development of sewerage systems. The name of the main collector of Rome's sewerage system is known all over the world: the *Cloaca Maxima* ("*Cloacina*" was the goddess of sewers). Its construction dates back to reign of *Tarquinius Priscus* (616–578 BC). The *Cloaca Maxima* combined three functions: wastewater removal, rainwater removal and swamp drainage [65]. The *Cloaca Maxima* presumably follows the course of an old ditch, but since it was insufficient to handle the flow of wastewater, it was enlarged in the next centuries, extended, and roofed over [2]. It was built on 700 years of evolving hydraulic engineering and architecture. It began as a monumental, open-air, freshwater channel, guiding streams through the newly levelled, paved, open space that would become the *Forum Romanum* [66]. The Cloaca Maxima started near the Forum Augustum and flowed into the Tiber near the Ponte Palatino. During the time of the emperors (31 BC to 193 AD), the main channel could be travelled by boat and could be entered via manholes, since it has a breadth up to 3.2 m and a height up to 4.2 m [67,68].

The Romans developed very advanced technology to sanitation, including baths, with flowing water, and underground sewers and drains. The drains of Rome were intended primarily to carry away runoff from storms and to flush streets. There are specific instances where direct connections were made to private homes and palaces, but these were the exceptions, for most of the houses did not have such

connections. The need for regular cleansing of the town and flushing of the sewers was well recognized by commissioner *Frontinus* of Rome, as indicated in his statement, "I desire that nobody shall conduct away any excess water without having received my permission or that of my representatives, for it is necessary that a part of the supply flowing from the water-castles shall be utilized not only for cleaning our city, but also for flushing the sewers" [69]. Sewer infrastructure throughout the town was essentially completed by *ca*. 100 AD; some direct connections of individual homes began to appear. Terracotta pipe was utilized. If a pipe had to withstand pressure, it was often fully embedded (e.g., sealed) in concrete, a practice that the Romans started. Sewer odors were a problem, since there were very few vents from the sewers. Any connections to public baths, or to the few houses that were connected, served as vents in the early years, making life interesting (odor-wise) in those facilities [7].

Much information about ancient Roman sewers can be drawn studying other known Roman towns such as Pompeii and Herculaneum, in nowadays Campania region, and Ostia, in nowadays Lazio region, all in Italy.

Pompeii had a scattered network of sewers. Rainwater and wastewater were primarily disposed of along the streets. Consequently, the streets would have contained some quantities of human waste [70]. Pompeii's street drains existed only in the vicinity of the Forum at the time of Vesuvius' eruption. The streets were a sort of open channel conveying water from public fountains, rainwater and sewage. The overflow from the cisterns and the road-side fountains and towers of the water distribution system would have assisted in removing both human and animal waste from the streets [71]. This practice required a significant water supply for Pompeii: this was assured by the Avella's aqueduct, before, and by a branch of the Aqua Augusta, after [72]. As shown in Figure 12, in the streets featured raised sidewalks (50–60 cm high) with stepping stones (the so called *pondera*) at the intersections to enable pedestrians to cross from one side to the other without stepping down [65,70,73].

Figure 12. Stepping stones (*pondera*) in Pompeii, in *Via dell'Abbondanza*.

Collection and disposal of wastewater was necessary not only for domestic activities but also for workshops. This is the case of the *fullonicae* (*i.e.*, where processes of cleaning clothes, finishing new cloth and maintaining or reconditioning old clothes took place), whose remains are visible in the archaeological site of Pompeii, as the famous *fullonica* of Stephanus [74]. In the basins of the *fullonica* there is a drainage channel running all the way through the house and then ending in the *Via dell'Abbondanza* [74], where, similarly to the other streets of Pompeii, in ancient times, there were water coming from the public fountains mixed with wastewater and each kind of domestic waste.

Herculaneum had a more systematic network of sewers than Pompeii. Rainwater and wastewater were directed away from the town by means of paved streets. The sewage system was constructed under the street along the *Cardines* (III, IV, and V) intersected by the *Decumanus Superior* and *Inferior*. In Herculaneum, the existence of discharge holes in the sidewalk under each *domus* of Cardine III suggests the presence of a sophisticated system of wastewater and rainwater discharge. The sewer system may have differentiated between rainwater (channelled through the sidewalks on the street) and wastewater (discharged into the sewer below street level) [70].

Ostia had a complete and uniform sewerage system that has been well preserved because it has always remained underground. The system was based on large sewers passing under the middle of the streets that functioned to channel wastewater collected from more little sewers exiting from the *domus* on both sides of the streets. The sewers had Cappuchin (consisting of large terracotta shingles) and barrel vaults [70].

7. Medieval Times

7.1. Early and High Middle Ages

It seems that the crisis in the maintenance of the sewers of the Roman cities occurred in the 3rd–4th centuries AD. Nevertheless some urban centers still functioned uninterruptedly until the 8th century in Italy, Spain, southern Gaul and the Rhineland, therefore the hydraulic constructions were maintained and were still operative [75] (p. 21). Some aqueducts and sewers functioned in spite of the gradual abandonment and degradation of the cities.

Such cities as Fano and Pavia in northern Italy were actually an exception in the European urban life scene, as the Roman sewers continued in use during the Early and High Middle Ages. This fact may suggest that these cities presented better hygienic conditions that any other contemporary town. A testimony, although dated the 14th century, refers to the sewer system in Pavia: "*Totius civitatis tam strate, quam latrinarum cuniculi, quibus omnes domus habundant, tempore pluviali per subterraneas et profundas cloacas emondantur, que omnes cloace cum testudinibus quasi pulcra hedificia sunt sub terra, et alicubi tam altas testudines habent, seu forces, ut possit per eas equus cum sessore transire*" [76] (pp. 13–23) (*i.e.*, "Both paved roads of the entire town and conduits of the toilets, which are abundant in all homes, are cleaned by means of the rain that runs into deep and subterranean sewers, and in general all the vaulted sewers are beautiful like underground buildings, and in some cases they have so high vaults that a horse with a knight can pass through them").

In spite of the examples mentioned above, the disintegrating of the urban administrative apparatus during the Early Middle Ages influenced the decline of the quality of the city life and one of the features of this process was the lack of maintenance and construction of the sewage system. Most

European cities lost their political and economic importance they had previously. Bologna, for example, was reduced from 70 to 25 ha, while within a vast city area of Trier a small number of inhabitants barely survived, who were insufficient to prevent the decline of the city. The inability to maintain and repair the Roman engineering legacy such as roads, bridges, aqueducts, reservoirs, harbors converted these kinds of structures into the mysterious manifestation of the supernatural powers. During the decay of city life, the major Roman engineering works were transformed within the collective imagination into "devil's bridges" built in order to challenge man and his heavenly protectors [75] (p. 29).

"The uncertainty between the fall of the Roman Empire and the Dark Ages"—this is how Leguay [77] (pp. 134–136) entitled one of the parts of his study. Certainly this is an appropriate title for defining the situation in a vast geographical area during the Early Middle Ages, which offers us a considerably inferior amount of written sources that hinders largely creation of an authentic historical portrait. In fact, J. P. Leguay wonders if the entrenched consideration that after the fall of the Roman Empire there was no system of sewage disposal is actually correct or it is widely accepted because of the historiographical inertia due to the lack of the data that would offer a distinct vision of Europe during these centuries. It seems that some of the Roman sewers, apart from those previously mentioned in Pavia and Fano, were still in use during the Early Middle Ages, as the citizens, governed by bishops, adapted some practices inherited from the Romans. According to the writings such as Gregory of Tours (d. 595), the Merovingians were busy paving the streets, so at least there was a concern for the urban comfort albeit minimal in some towns [77] (p. 135). Cassiodorus (d. 585) alluded to the drainage works undertaken by the authorities of Parma under the reign of Athalaric (d. 534); even his successors the Lombards apparently were also concerned to maintain the functioning of the city [78] (p. 141).

According to Leguay [77] (p. 136), the discovery of the authentic historical data of the Early and High Middle Ages depends on the number of researchers who deal with the search for information and not on the existing amount of the information. Given all the above, we can conclude that in some cities the sewer network, inherited from the Romans, remained effective. Nevertheless it remains much more difficult to find information on the private household sanitation. Analyzing Europe, composed almost exclusively of rural settlements due to the collapse of the city network, we must take into consideration the opinion of Pognon [79] (p. 286) because, according to him, it is impossible to believe that around the year 1000 in the small wooden castles there were any appropriate sanitation facilities. Most probably only the great lords in their castles and palaces possessed comforts probably similar to those of the important abbeys, but most of the wooden castles owned nothing but a trench dug around the castle which served as a dump place, although the location of the castle on a hill helped to get rid of filth quite easily.

At the same time, in the historiography of the Middle Ages it is widely accepted that the monasteries constituted examples of the exceptional hygienic situation compared to the coeval private houses and not just in the Early and High Middle Ages but also during later periods. According to Wright [80] (p. 50), the monasteries were the guardians of the hygienic practices and culture during the post-Roman period and also they were the pioneers in the water supply and sewerage constructions. In this sense we can refer to the monastery of Cluny (France), in which in the late 11th century there was constructed an inn with forty individual latrines and a worker was assigned to clean them regularly [81] (p. 62). Nevertheless, it is worth noting that in spite of the fact that after the fall of the Roman Empire

monasteries preserved some hygienic traditions, the general sanitary situation should not be overestimated. Usually in monasteries, according to the plans of Christchurch and Canterbury in England or St. Gallen in Switzerland, despite the presence of sanitation facilities their inhabitants expressed a rather reluctant attitude regarding the use of the bathroom, due to the conviction that living surrounded by dirt meant living in holiness [82] (p. 249) [83] (p. 55).

It should be said that the model of a cloister hygienic conditions was quite different from that of any town of that period and have to be studied in conjunction with a number of advantages that were vetoed to other people at the time: vast spaces with the inclusion of some watercourse and an absolute freedom to organize and distribute the edification of its dependencies. According to the usual distribution of the monasteries, the lavatory or the *reredorter* in the Anglo world was placed at the end of the bedroom and overlooking a river or at least a canal that ran from it and resumed it again later, a similar system to the Roman *forica*. A drain was located directly under the seats.

In conclusion, both because of their sanitation facilities and a network of water supply, the monasteries constituted a model for the time, all of which was beneficial, although we cannot know to what extent, to the health of its residents [77] (p. 31) [84] (p. 364) [85] (pp. 9–15).

7.2. The "Western" World

The Roman Empire fell in early AD along with the concepts of baths, toilets, sewage systems, and basic sanitation. Essentially, very little progress was made from *ca*. 300 AD through the early 19th century. Emphasis was on wars and very little on development and of course on sanitation and sewerage and drainage systems.

Burian and Edwards [86] argued that since during the Dark Ages few technological advances were made, let alone implemented, in Europe, urban infrastructure elements including urban drainage systems were not being improved. In their opinion, the prevailing public perspective of urban drainage during this time period was an unneeded service. However, Markham [87] stated that the medieval world was more conscious of sanitation than the other renaissance civilization, but it did not prevent Europe succumbing to bubonic plague. In fact, during the Middle Ages, epidemics raged through the majority of European cities.

In Medieval Europe, most people lived close to streams, rivers, or other water bodies, because water was not commonly brought into the urban area via aqueducts or pipes as had been done in Antiquity. Urban stormwater runoff and industrial wastewater were the principal waste discharges, mainly tanners and dyers [86]. As a matter of fact, an official investigation into the state of the Fleet River in London in 1307 AD concluded that the main cause of pollution was tanning waste and butchers' offal from Smithfield market [87]. Human faeces were collected and used in backyard gardens. Other wastes were typically stockpiled near the city or fed to pigs [86], in the case of organic waste.

The sewers implemented in Europe during the medieval times were simply open ditches that followed existing drainage pathways and often were directed along the center or roadways [86,88]. It is worth nothing that the name "sewer" derives its origin just in this period and properly from this latter configuration: *ca.* 1400 AD, "conduit," from Anglo-French *sewere*, Old North French *sewiere* "sluice from a pond" (13th century), literally "something that makes water flow", from shortened form of Gallo-Romance *exaquaria* (*cf.* Middle French *esseveur*), from Latin *ex*- "out" (see ex-) + *aquaria*, fem. of *aquarius* "pertaining to water," from *aqua* "water" [89].

Rivers in London and Paris were used as open sewers for centuries. Only in 1357, in London, a proclamation was issued forbidding the throwing of any sort of waste into the Thames or any other waterway [90–92].

In the late 12th or early 13th century, the King Philippe-Auguste has been the first to implement open sewers in Paris, France, in the middle of the newly paved streets [93]. In 1370, the provost Hughes Aubriot improved Paris' sewers: the open sewer of the *rue Montmartre* became underground and vaulted [94]. In the next years, the same work is done in three other areas of Paris [93].

It has been mentioned that London underground sewers might date back from the Roman period, channelling wastewater and storm runoff into the Thames River [92] (p. 63). The underground sewers of Church Street, in York, are also considered to be from the Roman period [95], most probably previous to the 2nd to 4th century AD [96] (p. 221). But, as pointed out by Rogers [97] (p. 133), "not all towns had sewers and it is important that we do not apply modern attitudes to urban sanitation to the Roman period".

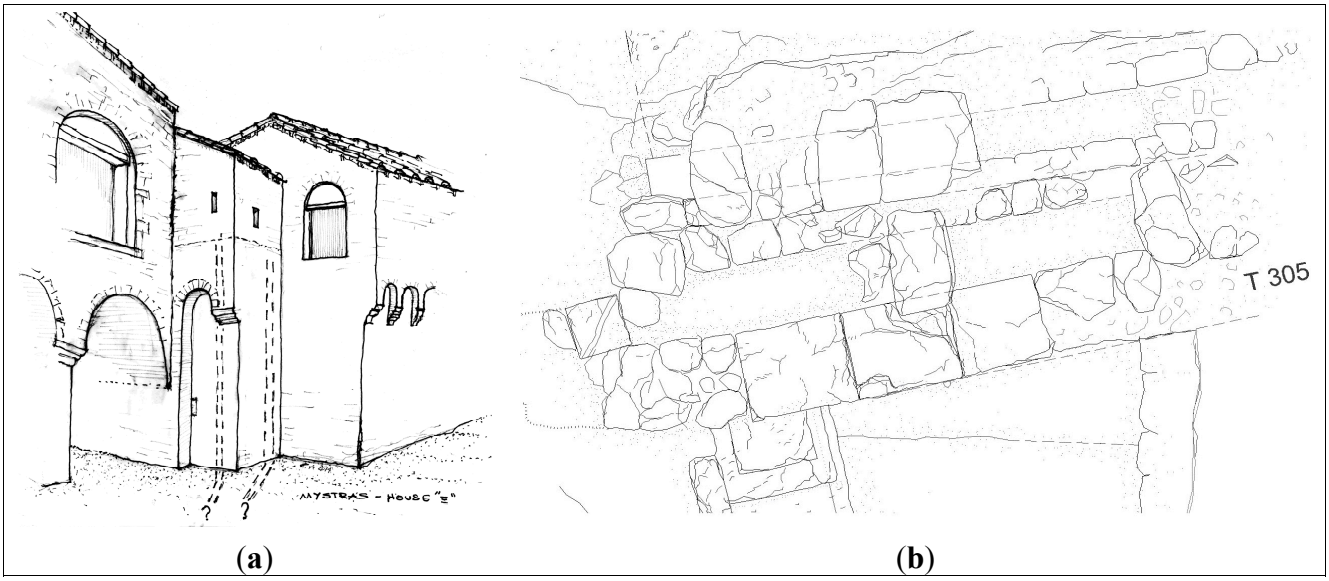
7.3. The "Byzantine" World

The ancient and Roman tradition, regarding sewerage, seems that had survived in the Eastern part of the Empire, which later was called Byzantine (at least till the *ca*. 6th–7th century AD), as it can be concluded by the surviving written sources as legislation codes, building regulations, *etc.* [98,99]. Moreover the continuation of these relevant to sewerage rules and legislation until the era of the dynasty of Macedonian Emperors (*ca.* 9th–11th century AD) testifies that constructions of that type continued up to that period. On the other hand, most of the scholars assume that during the last centuries of the Byzantine state the actual condition of the sewer network was not relevant to the contemporary detailed legislation about these sanitation matters and was much decayed or even extinct.

According to the written sources, it is documented that in the Byzantine cities existed central and secondary sewers and drains, neighborhood ducts network and domestic drainage for rainwater. Also the distinction between public and private sewers is evident, as well as the right of the inhabitants to connect their own sewerage to the central public ducts. The sewers of the ordinary houses were mostly of ceramic pipes and they were differentiated from the public ones due to their size and probably to their construction. Relevant references about residential cesspits conclude that there were also domestic sewers not connected to a public network. In addition there are clear references about separate domestic drains. After several detailed references it is also testified that there were vertical sewers—as in Figure 13a—serving the lavatories of the upper floors of the residential blocks. Despite all the regulations and codes it is concluded after the written descriptions of that era that the sewerage network of the capital Constantinople was not efficient enough. According to the scripts it can also be assumed that sewerage network existed only in town where the disposal of the wastewater in a river, lake or the sea was possible [98].

Unfortunately very few structures of that period survived either due to their low quality construction—as in Figure 13b—or to the destruction or incorporation to later networks. The limited remains of sewers in Mystras present mostly the remains of the sewers attached on the surviving buildings [100], and the few small fragments of sewers at the streets present impromptu stone slab covered constructions.

Figure 13. Byzantine times sewers: (**a**) Mystras. Lavatory towers incorporating the vertical sewers of the—according [100]—house (with permission of George Antoniou) and (**b**) Impromptu twin sewers in Kardamena, Kos.



The Byzantine tradition in the region—even though decayed and diminished—was followed with some improvements by the relevant structures of the Venetians, the Franks and generally the "Westerners" who ruled several areas around eastern Mediterranean. On the other hand the unstable and unsafe conditions of that era in that very region limited the establishment of more proper sewer networks and hygienic provisions, as it had already started in Western Europe.

7.4. Medieval Islamic Towns: The Case of Al-Andalus (Spain)

From the 8th to the 15th century part of the Spain territory formed the Muslim state of Al-Andalus. The borders of this unique state changed and its territory shrank gradually because of the continuous attacks and conquers of the Christian troops until its disappearance in 1492. As Fletcher [101] (p. 77) pointed out, Al-Andalus had been the richest, the best-governed, the most powerful, and the most renowned state in the western world. Apart from other aspects of the urban life, the sanitation of the towns of Al-Andalus can be considered significantly more advanced as that of the coeval Christians towns. The widespread presence of latrines in the majority of Andalusian houses, in spite of the wealth differences of their inhabitants, can be seen as a major advantage of domestic sanitation in Medieval Europe, very different from the Christian towns where neither latrines nor subterranean sewer systems were frequent.

In the Islamic Medieval towns, the absence of municipal authorities controlling public hygiene was substituted by the principle of common citizenship, reinforced by the Koranic injunction of not harming another Muslim.

The device of the latrine was composed from a bench with a groove in the middle, connected to a cesspit or a sewer. The Islamic latrine was different from the one used in the Christian territories because one had to squat and couldn't sit down nor be on foot. Within an Islamic house the privy was always a private and safeguarded place, with the entrance normally from the patio. Usually the room of the latrine was very small and most probably rather uncomfortable.

The evacuation of wastewater was relatively straightforward in rural settlements and small towns of the Islamic medieval towns of Spain—more than half the dwellings that were exhumed in Villa Vieja de Calasparra (Murcia), dating from between the tenth and the thirteenth centuries—had no latrine, and only three houses had their latrines connected to cesspools placed in the street [102] (pp. 163–175). Moreover, in some rural Andalusian settlements there were no latrines documented. Nevertheless, such settlements as *Siyāsa* (Cieza) and Saltés (Huelva) or the suburbs of Caliphal Cordoba demonstrate a most common solution of medieval sanitation consisting in latrines connected to cesspools [103–105] (pp. 219–294). In such settlements the rainwater was discharged directly onto the public street while the residual waters were accumulated within cesspits.

Although the most usual place for a cesspit was a street or a cul-de-sac, we can observe such uncommon locations as a stable, a courtyard or the entrance [106]. We can only guess that such unhygienic arrangements were made due to the lack of available space around the house as it is hard to explain it otherwise.

In an urban environment where there was enough space between the dwellings, where the citizens could have afforded to have private gardens at the back of the house, the existence of cesspits did not affected urban hygienic conditions, in spite of the fact that their cleaning must have provoked some disagreeable smells and contamination.

Apart from the more extensive use of cesspools, a sewer network was present in some medieval Muslim cities of Spain; the presence of sewers is documented through archaeological excavations and written sources. For instance, the presence of sewerage at the end of the 13th century is documented in Muslim Algeciras. One of the Christian prisoners that escaped from the city, while narrating his escape mentioned that he started running through a narrow street and then made his way into a sewer and reached the seashore where he was dumped into a dung heap [107] (pp. 31–38). Most probably the main city sewer discharged waste water into the sea and partially onto the seashore, where the prisoner happened to fall. In an overcrowded town, a sewer system implied a notable hygienic improvement.

Thanks to archaeological excavations, the town of Murcia offers an excellent example of a sewer network assembled in order to evacuate drain and wastewaters. Archaeological evidence shows that, at least from the eleventh century, this sanitation system was well organized and the use of cesspools was quite exceptional (although latrines connected to cesspools are observed in minor settlements of this region, such as La Villa Vieja de Calasparra and *Siyāsa* (Cieza)). In Murcia, the latrines were connected to small channels that emptied wastewater into canals located in nearby cul-de-sacs. After that, dirty water was conducted to public sewers that were buried beneath the streets and subsequently passed into huge underground canals to evacuate it outside the defensive walls of the city [108] (pp. 401–412). Other medieval Spanish towns such as Denia, Malaga, Almeria and Algeciras also had sewerage networks of greater or lesser importance [106].

The district of Portal de la Magdalena in the town of Lerida serves as an example of an urban area where a sanitation reform took place [109]. During the Caliphal period the inhabitants of the district made use of latrines connected to the cesspools that were installed in the streets and very close to the facades in order to discharge waste water as soon as possible. Nevertheless, during the 11th century, a fundamental urban reform took place in the district as a sewer network was installed while the cesspools were withdrawn. Not only all the inhabitants of the district must have been involved with such an important urban policy but also some sort of governmental support must have been offered.

The central part of the city where social, economic and religious life of the city was focused and where such significant buildings as the Great Mosque or the residence of the sovereign were placed, naturally received more attention and care in terms of cleanliness. In case of Cordoba we can see how a sewer net interconnected the central part of the city collecting the waste water from the edifice of ablutions of the Great Mosque, the residence of the sovereign or the public baths [110] (pp. 231–246). The sewers of major size collected used water from the net of minor drains in order to evacuate it directly to the river. The Muslim sewers of Cordoba were still visible until the first part of the 20th century when they were destructed by the city authorities. Today, despite the demolition of the sewers, part of the network is still being preserved beneath some of the current streets surrounding the Mosque of Cordoba. The canals made of sandstone slabs of different sizes were installed during the second half of the 9th century when the modifications of the Mosque took place.

The palatine town of *Madīnat al-Zahrā'* (Cordoba) serves as a perfect example of a settlement built with a previous well studied architectural plan where two subterranean pipe systems were designed for water supply and wastewater discharge. The models of this sophisticated sewer system, although the use of the hydraulic installations lasted only 75 years, must have been looked for in the Oriental Islamic world. The complexity of such sewer network that was capable to evacuate waste and rain water promptly was not a common characteristic of the towns in Al-Andalus. As we can observe in the majority of Andalusian towns, a rather simple small-scaled sewer network was used. It should be pointed out that normally only some districts of the town were provided with sewer network while the inhabitants of other urban areas, normally out of the city center, made use of latrines connected to cesspools. The installation and maintenance of sewers must have been costly and a technically complicated process that not all of the citizens could have afforded. The collaboration among neighbors was obligatory in order to have it functioning in the neighborhood, also the utilization of sewer network was not free of charge. When a citizen wanted to connect the waste pipe of his house to the public sewer, he had to pay a fee to the owners that set the sewer. The owners could deny the request if they observed that a new connection would damage their sewer. Although disputes arose from time to time, the jurists considered that all the users of the sewer bore responsibility for its cleanliness [111] (pp. 52–53) [112] (p. 116).

A sewer network could only function when a constant flow of water was produced. If there was no constant overflow the sewers would have clogged rapidly. Therefore we can observe how in Murcia water wells inside the courtyards were necessary elements in order to have the sewer network in function, as the citizens used its water to flush the latrine [108] (pp. 401–412).

Apart from the new-built sewer system the habitants all over the Medieval Islamic world made use of the hydraulic construction of the Roman world such as aqueducts or water channels, some of the Roman *cloacae* also were reused. Nevertheless, not always the original construction was preserved and adequately used. Sometimes the citizens of medieval towns reused only partially the inherited sewers, most frequently they perforated massive sandstone gutters to set up their cesspits directly on the cloaca as it occurred in Medieval Saragossa or connected a new drain to a Roman cloaca as documented in Cordoba [106] (p. 149).

When discussing the medieval sanitation system we should remark that rivers were used as *cloacae* during centuries. In Al-Andalus, in spite of the fact that river water was consumed for human needs, river courses were used as sewers and also as garbage disposal places. Nevertheless, the employment

of watercourses as open sewers had been common in the entire Islamic world, even in such cities as Damascus or al-Basra [106] (p. 275).

In spite of sanitation problems, which were common in medieval Islamic cities such as water contamination, accumulation of garbage within the city walls or the accumulation of cesspools nearby the living space, the existence of sewer networks in the urban environment along with the presence of a latrine within domestic spaces, demonstrate that medieval Islamic sanitation was much more advanced in comparison with the coeval Christian cities.

8. Modern Times—From the Old World to Modernity

8.1. From Mid-14th Century to 1900

In the rapidly growing Europe, cities of the High Middle Ages attempted to organise solid and liquid wastes removal. Wastewater disposal in Paris was unregulated until a decree of 1530 which required that each new house has to be equipped with a cesspool [113]. In 1636, a report mentioned 24 sewers in Paris, of which only 6 were covered, and every of them was clogged or ruined [94]. According to a law of the year 1721, property owners had to "pay for the cleaning of the covered sewers beneath their building" [86]. In 1736 and 1755, the development of the legislation continued in order to prevent dumping into the covered sewers. In 1789, Paris had about 26 km of sewers, and reservoirs were used to flush away the wastes blocked in the sewers [114], a technique already tested in 1740 by the provost Turgot [93]. During the 1830s, the lack of sanitation is alleged to be the main cause of the propagation of the cholera epidemic. Thus, the sewerage system is restored and enlarged after 1830, by the prefect of the Seine, Claude-Philibert Barthelot comte de Rambuteau. Henry Charles Emmery, head of the Paris sewer system from 1832 to 1839, improved the Paris sewers. He changed the open channels of the center of streets by underground gutters [86]. However, the system was insufficient and it was not able to assure a good operation. In 1853, Napoleon III appointed Georges Eugène Haussmann prefect of the Seine, who entrusted the hydraulic works to the French engineer Eugène Belgrand. Thus, in the early 1850s, G. Haussmann started to construct the new Parisian sewers, at the same time of the rationalization of the whole city. Construction included 600 km of new pipes and ducts, leaving only 15 km of the old sewerage built less than 20 years before. The sewers were 2.30 m high and 1.30 m wide, in order to collect both rain water, as well as domestic and industrial wastewater. In the main collectors, even larger (up to 4.40 m high and 5.60 m wide), rails for wagons for the cleaning of the channels were installed [2,115]. By 1870, over 560 km (348 miles) of new sewers were in service or under construction [94]. Even if the first attempts to treat Parisian wastewater started in the last 18th century [91], it is only at the end of the 19th century that wastewater valorization begun with the first "sewage farm" in Achere [116]. But, it's only in the 1930s that Paris agglomeration will get its first wastewater treatment plants [32].

Even if the common idea is to think that the concepts of baths, toilets, sewage systems, and basic sanitation felt with the Roman Empire in early AD, various studies have proved that the notions of cleanliness and sanitation were not absent from Medieval cities [86,92,117−120]. Indeed, in 1427, the first English public Acts about sewerage issue was delivered [121]. Latrines seemed to have been common during the medieval period in UK [92,117], but it is considered that Sir John Harrington

"invented" the water closet in 1589 [87]. The wastewater of medieval latrines of London overflowed into a cesspool, or directly into the waterways and then/or into the Thames River [120], despite the 1357 ban on waste dumping into the Thames River [92]. We can also suggest that some latrines probably consisted in a barrel type without outlet, as the one of 15th century Worcester [122]. Still, most of the time streets and gutters represented the main ways for wastewater disposal in medieval UK as in Scandinavia [118]. Between the late medieval period and the beginning of the 19th century, we did not find any data about sanitation in UK, which could mean that not any progress had been done in that period of time. In the 19th century, there were diffuse outbreaks of cholera [123]. Epidemics of this enteric disease in Europe is linked with colonization, since the first cholera outbreak appeared in 1817 in the delta of the Ganges, India, and then spread in East and South-East Asia [124]. Then, cholera epidemics occurred in London in 1831–1832, 1848–1849 and 1853–1854 [125]. In 1854, the British physician John Snow identified the Broad Street pump as the source of the outbreak [2,126]. Thus, even if it was compulsory for every London house to be connected to the sewers since the 1840s, that sanitarian development did not stop the progress of enteric disease, neither to the "Great Stink" to happen in 1858 [125]. Moreover, it is considered that the popularity of the water closet in the 1800s became a public health issue [91]. Effectively, because of the large volume of water introduced into the cesspits, the surrounding soils became waterlogged [127]. And then, when the water closet was connected to the sewers, it made the sewers overflowed [125]. It is estimated that between 1850 and 1856, the water volume of London sewers almost doubled due to the massive utilization of that facility [2,91,128]. In 1842, Edwin Chadwick is the first to have suggested a system where wastewater conveyance is separated from surface runoff [2,129]. With the 1848 Public Health Act, the Metropolitan Commission of Sewers is formed [125], and the Central Board of Health is established, where Chadwick is posted as commissioner [130]. From 1859 to 1867, Bazalgette, the chief engineer of the Metropolitan Board of Works in London, developed a great project for the collection of the wastewater of every household in the first sewerage system of the city. The system was based on 139 km of collectors passing on either side of the Thames, linked to the 2100 km of sewers, built *ex novo* or renewed, passing beneath the streets of central London [115]. The construction of the London sewerage system involved a first extensive use of Portland cement [2,131].

In Hamburg, Germany, the first comprehensive planned sewerage system for a major city was constructed in 1843. During May 1842, a severe fire destroyed a large part of the city and William Lindley, a British engineer, was commissioned to plan and design the system. In the city of Frankfurt, sewers have been built in 1867. The construction dates of the sewer systems in other German cities are: Danzing in 1871, Berlin in 1873, Breslau in 1877, München in 1881, Köln in 1881, *etc.* The first sewage treatment plant in Germany was constructed in Frankfurt in 1887 [132].

In the Danish capital Copenhagen, the sewers have been constructed in 1857, and improved between 1860 and 1885 so that wastewater and surface runoff were channelized into the harbour. But, because of that unhealthy management of the wastewater, new equipment has been implemented from 1893 to 1903. This work consisted of new sewers which collected the effluents along the harbour, and pumped them into the Sound [133].

In 1899 an investigation is done in Italy, and it shown that almost all major cities were connected to a sewer system [32]. But, only the sewers of the cities of Milan, Turin and Udine were considered as efficient. Indeed, the sewers of the cities of the southern part of the country (Syracuse, Catania,

Caltanissetta, Reggio Calabria, Catanzaro, Cosenza, Potenza, Bari, Lecce, Avellino and Caserta) and of Rome, Naples, Palermo and Messina were inefficient [134].

Thus, between the Middle Ages and the 20th century, the sanitary sewers have gone through different stages of development. The basic principles regarding planning, operation and management practices were developed in various European cities mainly during the first half of the 19th century, and improved in a rationalized that was after 1850. It is at the end of the 19th century that European colonies will get sewers systems, for the same public health reasons, but later than in Europe [130]. At the end of the 19th century, British and French India followed the legislation of their colonizers. During the first decade of the 20th century, the sewers of Calcutta, the then British India capital, are constructed [135]. The first sewers of Pondicherry, the main city of French India, are built in the 1930s, but drains had been implemented during the 18th century, and law about waste dumping at the end of the 19th century [136]. One has to notice that in 1911, New York was not equipped with a sewage system [137].

8.2. Modern Times

During the previous years, the "state-of-the-art" for sewage disposal had advanced considerably more than that for sewage collection and conveyance. Cities and towns had the benefit of knowing the actual connection between sewage and the sources of drinking water (e.g., the adverse potential impact on their health/welfare). That knowledge resulted in great strides being made in collecting and conveying sewage away from people's homes, and in treating the sewage prior to its discharge either into their source of potable water or at a point near their source.

From the second half of the twentieth century, the need for proper sewer systems began to be regulated by specific laws in all developed countries, even if there are many areas (especially in rural contexts) that still lack of sewerage systems.

Three main types of collection systems are today used for the removal of wastewater and stormwater: (a) sanitary wastewater collection systems, (b) combined wastewater and stormwater collection systems, and (c) stormwater collection systems. The use of separate sanitary collection systems spreads very fast in the developed world, whilst combined wastewater and stormwater collection systems are dominant in the developing world. Nevertheless, the differences in the principles applied in these wastewater collection systems are minimal.

In terms of direction of the collectors, the sewer systems developed in modern times are mainly of four types: (1) with a longitudinal path, with collectors running parallel to the longest dimension of the town; (2) with a transversal path, with short collectors across the city and with many separate effluents; (3) with radial collectors coming from different parts of the town and converging to a unique point from which the effluent commence; (4) with separate systems, with the town divided into two or more areas at different levels, each of which with its own network of drains.

The shape of the channel section can be very variable. For example, circular profiles (they allow to build the sewers using pipes) oval profiles and mixed profiles (usually a rectangular excavation with a small circular channel on the bottom) are typically used for small sewer systems.

Pumping systems developed with the advent and spread of electricity would deserve a separate description that is out of the scopes of this article. The use of the pumps can produce large expenditures

of energy, but they are very helpful where there are high differences in height from on area to another of the town. In this sense, the availability of pumps in sewer systems has certainly simplified the complexity of the paths of the drains, also achieving cost savings. In general, pump systems are very delicate and require accurate operation and maintenance.

With modern times, the problem of wastewater management commences to be seen not only as a simple collection and transport away from urbanized areas. Indeed, scholars and technicians started to evaluate the impacts of wastewater collection and disposal on the environment and in particular on the surface and groundwater. The first wastewater treatment systems appeared at the beginning of the century, namely the trickling filters [138], although the true protagonist of the last century was the activated sludge system [68]. Given the close interdependence between sewers, treatment plant and receiving water bodies, the principal challenge of the modern times has been studying them with a systematic and unified approach.

Before giving some conclusive remarks, it is important to briefly discuss some emerging trends and perspectives. This will allow us to consider the performed study of sewers development in a perspective that connect past with future.

9. Emerging Trends and Perspectives

The future collecting and conveying sewage will be governed by the following macro drivers:

(a) *Population Growth.* It is estimated that by 2050 the world population will increase by an additional 2 billion people [139] (e.g., a city of ~145000 every day), particularly in developing world that is already suffering from inadequate water resources and degraded environments. Sewerage and drainage systems will thus play a vital role in future urban planning and should be reconsidered (e.g., they should highly decentralized, reduced their lengths, become more intense, and increasing their diameter).

(b) *Urbanization.* The great majority of these additional people will settle in urban areas further stressing the pollution pressures and health risks in these areas. In many cases it will not be possible to simply extend existing centralized water and wastewater systems to cope with the extra water demand and waste loads. The increasing volume of wastewater and the inadequate infrastructure and management systems will be at the heart of the wastewater crisis [140]. The expected increase in urbanization will have series impacts to the future wastewater management and especially to sewers infrastructure. Therefore, an expected increase in decentralized self-supporting systems will emerge [141]. Collecting and conveying sewage improves their resilience and avoids major social dislocation and economic loss. This will be a major challenge for developing countries with limited financial resources to cope with such a scenario.

(c) *Climate Change (variability).* Under the global warming scenario it is predicted that the world will experience more extreme climatic conditions (bigger floods and more severe droughts) [142]. According to U.N. [143], "There are also cities that are on sites that are or were relatively safe without climate change, but that now face new levels of risk". Specifically, an increase in heavy rainfalls may affect the capacity and maintenance of storm water, drainage, and sewerage infrastructure [144]. In some regions of the world the problems of floods and droughts will be felt more strongly than in others. For example, the geographical distribution of flood risk is heavily concentrated, regarding Asia, in India, Bangladesh, and China, causing high human and material losses (Brouwer *et.al.*, 2007; Dash *et al.*, 2007;

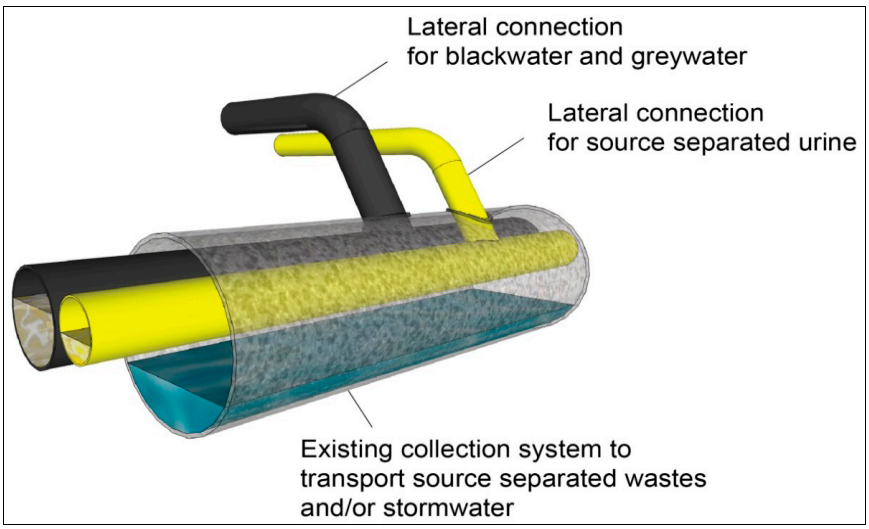
Shen *et.al*., 2008 as cited at [145] (p. 274)). Concerning Europe, the regions most prone to a rise in flood frequencies are northern to northeastern Europe (Sweden, Finland and northern Russia), while southern and southeastern Europe (Portugal, Spain, western France, Italy and most of southeastern Europe) show significant increases in drought frequencies [146].

Many of the structures, supply sources, facilities and wastewater disposal mechanisms are vulnerable to adverse impacts from climate variability [147]. The future collecting and conveying sewage as well the sewage disposal systems should be able to adapt in such new urban environment, especially in the coastal areas [141].

(d) *Ageing Infrastructure Assets.* Many networks and installations in mature economies are ageing and deteriorating. In European Union, the Member States have to upgrading their water and wastewater treatment systems to comply with EU environmental legislation. However, in Eastern Europe, Caucasus and Central Asia, many urban water systems are in poor condition, with no similar plans for upgrades, while in developing and emerging market economies, the pace of growth and urbanization, combined with rising environmental expectations, is creating the need for costly new investments [148].

This will present both a challenge and an opportunity on how to re-configure the sewers as well as financing of water and wastewater infrastructure to meet the future challenges, e.g., the existing wastewater collection system should be modified to be adapted to the source separated resource streams (Figure 14).

Figure 14. Use of existing collection system for source separated resource streams [141] (with permission of G. Tchobanoglous).



Nowadays, the ageing of the wastewater and sewer infrastructure is one of the most important issues facing the water industry followed closely by managing capital costs. Probably, the best way to address ageing infrastructure assets—an ongoing problem—is to analyze system needs and create long-term plans.

In addition to the aging of the sewers, the flow rates of sewage have decreased over the past decade and will continue to decrease in the future resulting to: (i) increased corrosion; (ii) most conventional gravity sewer design equations will no longer be suitable; and (iii) increased mass concentration loading factors have impacted wastewater treatment facilities.

(e) *Water Energy Nexus.* With existing sewerage and drainage systems the search for new ideas is forcing wastewater utilities across the globe to implement a range of higher energy sources such long

distance networks and sewage pumping. As well as adding to the cost of sewage collection and conveyance infrastructure is also contributing to the energy footprint and thus contributing to the climate change problem [149]. The question many water managers are now asking is: have we solved one problem and unintentionally created another one? There is a strong correlation between energy and wastewater collection, treatment and reuse and it is important that in delivering solutions in a variable climate world proper consideration is given to the relationship between wastewater and energy use. In the case of wastewater collection and conveyance opportunities exist to produce energy and thus reduce the overall energy footprint, e.g., sewers should also adapted to recover of heat from wastewater with heat pump.

10. Conclusions

Drains in the streets are known since the early Mesopotamian Empire in Iraq (*ca.* 4000–2500 BC). However, well organized and operated sewerage and drainage systems are not achievements of present-day engineers but date back to the Bronze Age, more than five thousand years ago [1]. These developments were driven by the necessities to make efficient use of natural resources, to make civilizations more resistant to destructive natural elements, and to improve the standards of life, both at public and private level. During the Bronze Ages two well known civilizations: (a) Minoans in the island of Crete (*ca.* 3200–1100 BC) and (b) Harappan civilization (*ca.* 3200–1900 BC) in Indus valley developed sophisticate, comfortable, and hygienic lifestyle, as manifested from long term very efficient sewerage systems, bathrooms and flushing toilets, which can only be compared to the techniques developed in Europe and North America a century and half ago.

Through the exploration of the development of the sewerage systems through millennia, it is evident that the cultural, social and economic 'peaks' of the human civilization across the globe were accompanied by sanitation improvements, including proper and well-functioning sewers. On the other hand during most of the Dark Ages in history the relevant hygienic provisions decreased and often disappeared in several parts of the world. Despite that it could be concluded that much of the relevant knowledge of the previous eras survived in some ways within the technical tradition of each specific greater region, and reappear when the cultural and economic capabilities permit it. Moreover it is almost common in most cases that these kinds of sanitation constructions were spreading to a significant majority of the urban population.

In addition to the technical issues, it seems that the importance of the application of sanitation principles at the past times was not inferior to nowadays, taking into account the technical capabilities of each era. Moreover, this review demonstrates how basic, techniques can tackle major societal, and environmental issues, such as urban wastewater management [150]. The evolution of the field of wastewater collection and treatment is the story of health and environmental concerns, especially as the size of the cities increased. More than 2.6 billion people do not use improved sanitation and unprotected environment, thus there is a huge need for sustainable and cost-effective water supply and sanitation facilities, particularly in cities of the developing world [151]. Applicability of selected ancient technologies for the contemporary developing world should be seriously considered.

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Author Contributions

Each author contributed depending on his/her Country of origin. Giovanni De Feo conceived and designed the study with Andreas N. Angelakis, while each single author collected and analysed the data useful for the Section/s related to his/her Country of origin.

Conflict of Interest

The authors declare no conflict of interest.

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