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Review

The Evolution of Agricultural Drainage from the Earliest Times to the Present

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Abstract: Agricultural developments require changes in land surface and subsurface hydraulic functions as protection from floods, reclamation of flooded land, irrigation, and drainage. Drainage of agricultural land has a long history and apparently traces back to the earliest civilizations of Mesopotamia and Iran before 4000 BC. In the Eastern Mediterranean, the Minoan and Mycenaean civilizations developed techniques and strategies of drainage of agricultural lands from the middle of the 2nd millennium BC. After the collapse of the Aegean Bronze-age civilizations, society building and agricultural innovation in the archaic and Classical periods (ca. 800–300 BC) included successful attempts at controlling drainage and irrigation techniques. In addition, China, India, and Mesoamerica have extensive histories of drainage. The aim of this review paper is to trace the evolution of the main foundings on agricultural drainage technologies through the centuries until the present. This historical review reveals valuable insights into ancient hydraulic technologies as well as irrigation and drainage management that will help to find bright horizons for sustainable agriculture in future.

Keywords: agricultural drainage; irrigation; land reclamation; water and civilization; sustainable drainage

1. Prolegomena

The term “drainage” implies removal of a liquid. For drainage scientists, that liquid is water, while in medical sciences, the term may be used to refer to bodily fluids. In this context, Luthin [1] considered “drainage” as a word with many meanings. For instance, it is possible to ascribe the drainage of an area to the network of its streams and surface waterways. However, in subsurface hydrology, the term "drainage" is used to indicate groundwater drainage or the seepage through an aquifer. As Oosterbaan [2] pointed out, "when we limit ourselves to land drainage the term has still, many different meanings". In addition, he underlines that the different perceptions may result in confusion "when specilasts are talking the subject of drainage, particularly if they come from various disciplines", and he ends up concluding: "the different interpretations make it difficult to give an unambiguous definition of what "drainage", "land drainage" or "agricultural land drainage" is."

Here, our primary interest is agricultural drainage, and consequently, our attention is focused on the removal of excess water and materials from the farm to improve crop growth, involving the removal of dissolved salts from the soil by means of conduits or other water conveying devices. Moreover, according to the ICID (International Committee of Irrigation and Drainage) drainage is *the removal of excess surface or groundwater from any area, naturally or by virtue of man-made surface or sub-surface conduits, has four main functions: creating well drained arable lands, preventing salinization of the soils, lowering of groundwater table and removal of accumulated salts or toxic elements* [3].

Characteristic examples of past drainage technologies and practices developed by our ancestors in several regions of the world are remarkably similar to the modern standards of drainage. We address the evolution of drainage, which took place in the major civilization of the past, and the methods and means used to drain the land are considered in a combined geographic and chronologic perspective. Insights into drainage technologies in antiquity, the medieval ages, and modern periods with their properties of durability, adaptability to the environment, and sustainability are prepared, as well as a review of water technologies in major civilizations. Following this synthesis is a timeline clarifying the hallmarks of agricultural drainage of the past 10,000 years. The scope of the article is not confined to the suggestion of what is known today about the act of drainage, related technologies, and their uses worldwide. Rather, this paper displays characteristic examples of drainage enterprises in selected fields, which chronologically extend from prehistorical times to the modern era and geographically from the Asia, Europe, and South America. Moreover, in the final section, we deal with the potential of our findings, including the vexing question of how the presented examples of drainage technologies and irrigation water management in the past hold the potential of becoming important for present and future developments in water engineering. We believe that this past experience in agricultural drainage is now underpinning modern achievements in water drainage engineering and is a good example of how *the past is the key for the future*.

During periods of low agricultural interest, small drainage work is accomplished, and study activity declines in these periods as well. Practices used in previous prosperous periods lie idle and are forgotten. Then, with a return to high agricultural interest, interest in agricultural water management and in particular drainage also resumes, but the old approaches have to be redeveloped. Luthin [1] reported that the reason for this is that one frequently sees articles in "popular magazines describing one new method of drainage that has just been invented"; it may very well be a recycling of already known principles of drainage used previously during, say, the early Mesopotamian, Hellenic or Chinese civilizations. Today, we use land drainage worldwide, and it is criticized severely by some and recommended by others [4]. Further, drainage technology has improved considerably, in parallel with the general scientific and technical progress of our civilization [5]. Nonetheless, in this context, past knowledge of drainage constantly inspires innovative rethinking of future drainage strategies. As Luthin [1] pointed out: "The drainage is maybeas old as the art of agriculture." The earliest evidence for artificial water management (irrigation and drainage) from Iran is from around 4000 BC [6–8]. In Mesopotamia, concerns over inefficient application of irrigation and on the cropping management of weed in some years prompted development of techniques to control the depths of the water table. Cultivation of the deep-rooted crops shoq (Proserpina stephanis) and agul (Alhagi maurorum) helped to achieve this control coupled with maintenance of a severe dry area that prevented the rise of salts via capillary movement [9].

Moreover, as early as in the third millennium BC, drainage systems were installed in Ancient Egypt, China, and India [5]. Archaeological investigations identified evidence of serious drainage problems that developed in irrigated areas; and many have argued that the major reason for the decline of some historical civilizations that relied on irrigation was their problems with heeding drainage hazards [10]. For example, some historians believe that the Sumerian civilization fell due to poor irrigation and drainage management [11]. Specifically, large-scale salinization made farmlands unproductive, and this contributed to the collapse of the Empire. However, there is some evidence that in irrigated lands, the need to have drainage systems and waterlogging control was understood in earlier times. Moreover, the first evidence of soil and water salinization control via leaching and construction of drainage systems in Iraq dates back to ca. 2400 BC.

Agriculture in Greece and the Aegean developed during Minoan and Mycenaean times. Here, profound developments in agriculture were responsible for increasing agricultural productivity and growth of populations. The Minoans in Crete and an unknown civilization in the Indus valley (Harappans) were probably the leaders in the development of drainage practices. In addition, some archeological evidence suggests that Incas and Mayans used subsurface drainage [12].

Irrigation and probably drainage systems appeared in Minoan Crete during the Neopalatial period (ca. 1740–1450 BC) when an extended drought period prevailed [13]. In addition, the impressive remnants of the Mycenaean hydraulic works at Lake Kopais in central Greece shows important land reclamation work of prehistoric Hellenic times. However, in spite of the minor and extended surveys of sites, the picture of ancient drainage efforts at Kopais remains ambiguous [14].

There is some evidence of similar hydraulic technologies to facilitate urban water management developed by Minoans and Mycenaeans and the other civilizations such as Egyptians, Etruscans, Dorians, Archaic, and Classical Greece [15]. Herodotus, a Greek historian of 5th century BC, based on priests' information of that period, wrote (Herodotus II) about the drainage works that Min (also spelled Mena, Menes, Meni) (ca. 3200–3000 BC), the first king of a unified Egypt, raised to protect the city of Memphis from floods. Classical Greeks inherited the Minoan urban drainage technologies and extended them further, mainly through changing their scale from very small to very large and implementing them to rural and urban sectors. Subsequent Hellenic, Hellenistic, and Roman engagements with and refinement of water management took place to aid agricultural production and land reclamation throughout the 'Hellenic speaking world' and the Roman Empire. However, the importance of soil properties as a basis of drainage design and the advantages of using deep covered drains under certain circumstances was recognized during the Classical and Hellenistic period (ca. 480–67 BC). Allegedly, attempts at draining Lake Kopais commenced during the Hellenistic period, and thereafter, the Romans extended the scale of the hydraulic works in the region. Until recently, however, the practices developed by Hellenes and Romans saw only limited improvements.

In ancient China, irrigation, drainage, and controlling floods have a history dating to around 3000 BC [16]. Initially, drainage engineering was probably for the sake of water conservation as part of the development of Northern China during the Pre-Qin Period (ca. 2000–221 BC). The central area of the alluvial plain at the lower reaches of the Yellow river (now the Henan and Shandong provinces) with flat terrain and abundant water was naturally the most suitable for agriculture. Dry farming in Northern China included tolerance to drought and drought-'resistant' crops like common milletand foxtail millet. In the Northern Wei dynasty (386–534 AD), the concept of a drainage channel system with reference to the large-scale waterlogging [17] was considered in the Youzhou province (presently downstream of the Haihe river basin). In addition, during the period from 1122 BC to 220 AD, saline-alkali soils in Northern China and in the Wei-Ho Plain were ameliorated with the application of proper irrigation and drainage systems, via leaching, rice planting, and through silting from historical floods [18].

During the Medieval period, marshes in England were drained to stabilize and increase agricultural production. These actions were not accepted by the fishermen and fowlers, who saw their livelihood threatened [4]. Interest in drainage declined until the 19th century, when the activity was renewed in the USA and Europe. In the USA, early interest was not restricted to the development and the enhancement of agricultural production but also stressed human health concerns, such as the draining of Central Park in New York City in 1858 [4].

A tile drainage system was implemented in 1620 in the Convent Garden at Maubeuge, France, but this event did not spur widespread adoption of the concept [1]. After two centuries, however, in 1810, a similar project had its origin in England on the estate of Sir James Graham in Northumberland. During the 16th, 17th, and 18th centuries, drainage techniques spread throughout Europe, Russia [19], and the USA [20]. Early in the 19th century, the invention of the steam engine brought a considerable enhancement in pumping capacity, enabling the reclamation of some large lakes, like the 15,000 ha Haarlemmermeer located southwest of Amsterdam in the Netherlands in 1852 [21]. Moreover, the abovementioned drainage project of Lake Kopais did not succeed until technological advancements of the 19th century were available.

According to Donnan [10], in the 17th century, closed drains were introduced in England, and in 1810, clay tiles started to be used but by 1830 were replaced with concrete pipes made with Portland cement. The first mechanically manufactured production of drainpipes took place in England, and from there, it spread across Europe and into the USA by the mid-19th century [19]. In 1890, excavating and trenching machines driven by steam engines made their advent, and in 1906, dragline machines made their appearance in the USA [22]. In the 20th century, the appearance of fuel engines led to the development of high-speed installation techniques of subsurface drains with trenching or trenchless machines [23]. In 1940, clay tiles gave way to thick walled, smooth, rigid plastic pipes, or bituminous fiber pipes [24,25], later replaced by corrugated PVC and polyethylene tubing in the 1960s [21].

For centuries, land drainage was a practice based on local experience, which gradually developed into an art with wider applicability. The theoretical development of the modern sciences of drainage may be considered to have started only 158 years ago in France under the direction of French engineering Henry Philibert Gaspard Darcy (1803–1858), who conducted column experiments [26] that established what has become known as Darcy's law. Based on Darcy's law, drainage theories developed that allowed land drainage to become an important field of research. Although these theories form the basis of contemporary designs for agricultural land drainage systems even today, they cannot determine beforehand a unique theoretical solution for a specific land drainage problem. Thus, as Bos and Boers [21] noted, "sound engineering judgment on the spot is still needed and will remain so".

Rapid technological progress in the twentieth century created a disregard for past water technologies that were considered to be far behind contemporary ones. There is a great deal of unresolved problems related to drainage systems–past and present—and especially to those used in agricultural lands. For example, in the past, drainage systems were anticipated to function for a long life, though with few follow-up studies [24,25], and with little consideration given to changes in future climate or farming practices. However, this will not be so in the years to come, because global warming and the greenhouse effect necessitate development of new approaches to a changed set of drainage issues. Therefore, the operating rules, the management policies, the planning principles, and the design criteria for new drainage systems should be re-examined. While climatic variability is expected to have significant impacts on drainage systems, there remains great uncertainty as to the climate impacts in the different geographic scales of interest and how these affect the drainage development process. Moreover, in developing countries, drainage development is often constrained because of the lack of public support policies, institutional frameworks, and professional cadres [27].

Although drainage is a very important environmental topic and a main factor in water resource management, for many years, it has been a 'forgotten agent' in water resources management, because drainage is considered by some as simply "an expensive solution to bad irrigation practices". However, this consideration overlooks the role of drainage control of shallow water tables (retention and removal of water) associated with water resources and environmental management. Consequently, drainage is a basic key in: (a) flood management, (b) securing farm productivity, and (c) improving local sanitary conditions [28]. It is understood that land drainage and soil amelioration techniques are fundamental to efficient agriculture and the preservation of biodiversity. Next, we explore the evolution and process of the drainage from the earliest times to the present and the lessons learned from history to offer new solutions to water risk-management strategies in current agriculture.

2. Prehistorical Times

2.1. Prehistoric Civilizations in Iran (ca. 8000 BC–651 AD)

Archaeologists confirm that numerous sites in modern-day Iran and Iraq (Mesopotamia) show evidence that a vast network of early Sumerians constituted the establishment of the first urban settlements, redefining the origins of modern civilization. Moreover, the implementation of water management systems became a distinct hallmark of these societies from around 5500 to 3200 BC. In addition, city regions were network nodes of societies and central junctions to different types of water flow [29]. According to Carl Lamberg-Karlovsky of Harvard University, the Jiroft site dates back to ca. 8000–4800 BC, signifying that the site and its environs were once home to a long-lived culture whose livelihood depended on water management systems and palm cultivation [6–8]. Similar observations and conclusions were made on Hagmataneh hill in Hamadan and Southwestern Iran, which date to ca. 5000–350 BC and ca. 6000 BC–639 AD, respectively [30,31].

Gillmore et al. [32] presented (Figure 1) evidence of a cross-section channel in the shape of a triangular with dimensions of 24 cm in depth and 1 m in width in an artificial water management installation on the Tepe Pardis at the Tehran Plain belongs to Late Neolithic (ca. 5220–4990 BC). Ostensibly, this may represent the earliest instance of water effort for drainage usage in Iran and possibly throughout the world (for drainage usage). The archaeologist in charge of the study interpreted it as an artificial system using infill-deposits, which shows times of shallow and relatively quiet flow, as well as times of occasional episodes and drying-out of larger flows [32]. This boosts the probability of a double use of the channel for both irrigation and drainage purposes (i.e., irrigation for drought seasons and drainage for wet seasons). Tepe Pardis is in the Central Plateau of Iran, Jaj Rud. The Jaj Rud catchment is located in Elburz Mountains and the watershed feeds water and sediment to a fan of more than 2500 km^2, which extends from the southern borders of the mountains, by the densely settled Tehran plain, down to a kavir or salty desert [33]. Gillmore et al. [32] strongly suggested which 6th millennium farmers who lived at Tepe Pardis were irrigating (and draining) the lands, and this context complements the evidence of early irrigation systems from Choga Mami in Iraq.

Figure 1. Position of triangular shaped water management channel in Iran (ca. 5220–4990 BC) [32].

The Susiana Plain in Southwestern Iran was a major developmental center for early complex agriculture; probably because farmers could choose between dry and irrigated farming, and there was ready access to trade routes from the Persian Gulf to the Iranian plateau across the Susiana. The evidence from the ancient Susiana has been augmented by comparison to other zones in ancient

Iran, albeit from the 'Initial Village period' ca. before 5000 BC identified by [34]. Southwest of Iran, east of the Tigris river, between the Dez and Karun rivers, approximately 75 km from the place where they join, the city of Chogha Mish flourished. This dry farming region did not have major channel irrigation before around ca. 1500 BC. However, in the Protoliterate time (ca. 3400–2900 BC), it was a "planned town with several streets, sewers and drainage canals, side alleys, workshops, public and private buildings, and water wells and cesspools". In this region, clay soil pipes and baked clay bricks were used as drainage systems, as shown in Figure 2 [35–37].

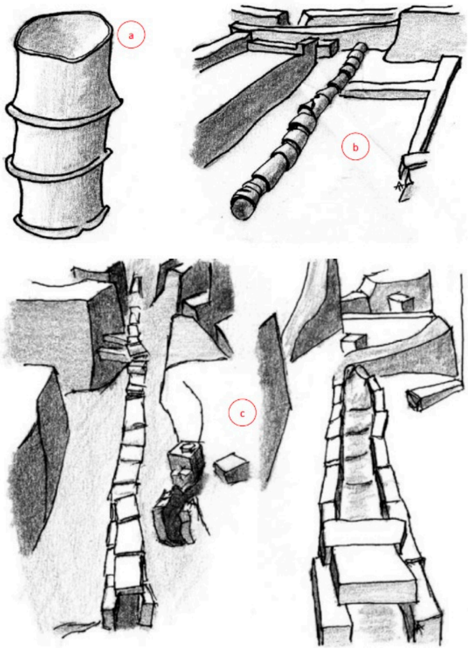

Figure 2. Schematic diagram of drainpipes found in Iran. (**a**) Old Elamite period (ca. 2700–1600 BC), (**b**) Protoliterary period (ca. 3400–2900 BC), and (**c**) drainage canalization made from baked clay bricks (ca. 3400–2900 BC) [35–37].

The qanat is the other ancient hydraulic structure used to irrigate and drain the agricultural lands in Iran. Although the qanat is widely known as an irrigation system, several studies underline the importance of this method for drainage of agricultural lands as well [38–40]. The history of qanats is not still determined; however. the qanat of Jopar, near Kerman (which is associated with the worship of the water goddess called Anahita) may date as far back as ca. 1200 BC. Similarly, studies in the northwest of Iran have established the presence of qanats as far back as ca. 800 BC [41]. In about ca. 525 BC, qanats were used at the coastal margins of the Persian Gulf [42]. English [43] and Stiros [44] also stated that qanats first emerged in Iran about 3000 years ago when Persian people began to settle as farmers, to worship only one god called Ahuramazda, and to conquer the Old World (mainly Mesopotamia). It is believed that the use of qanats originated in Iran [45–47] because this region had some of the oldest mining and metallurgical sectors in the world and that mining knowledge included constructing qanats from an early date [48].

2.2. Eshnunna/Babylonia and the Mesopotamian Empire (ca. 4000–2500 BC)

Farmers in ancient Babylonia drained wet soils for crop production. The improvement and especially the drainage of farms for obtaining high and crop yields became a human profession at that time. From the Neolithic period forward, domestication of wild animals began, and the appearance of primitive stone instruments to use in farms made it possible for persons to manage the first settlements [49]. In ancient Mesopotamia, the first settlements were along the two rivers of Tigris and Euphrates, where periodically flooded lands produced high yields without any artificial measures (e.g., appliance of fertilizers). However, as the population grew, lack of available land on flood areas forced people to think about the less fertile lands deprived of vivifying floods. In such cases, the two well-known land improvement practices—irrigation and flooding—were soon supplemented through drainage [49].

2.3. Minoan Era (ca. 3200–1100 BC)

Most rural development requires water projects, including that for flood protection of agricultural land, land drainage, and recovery. Furthermore, in the Mediterranean climate, irrigation is essential towards maintenance of many crops, and hydraulic projects are required for the collection, storage, transportation, and irrigation during the dry season, especially in regions with water scarcity. Even in th present times of California to Greece, agricultural irrigation uses 80%–85% of total water consumption. To ensure that water supply and delivery is adequate for irrigation scheduling and water conservation, hydraulic structural controls are needed at multiple scales. Similarly, civilizations of ancient Crete developed significant technological tools for collecting, storing, and transporting water to farmland to protect against floods and increase crop productivity [50]. Most likely, agricultural development in Greece is rooted in Minoan civilization. Population growth combined with economic and technological development contributed to increased agricultural productivity [51,52].

During the Minoan Era, agricultural development in Crete was necessary to support the dramatic demographic increase/population growth. According to Homer, Crete had 90 cities, of which Knossos was the largest and most important. During the Neopalatial (ca. 1700–1400 BC) period, Knossos developed into a large city whose population to judge by the surrounding satellite buildings like the "Little Palace", the "Royal Villa" and the "South House" and adjacent cemeteries, must have been no less than 100,000 inhabitants. At that time, other Minoan settlements were highly developed, e.g., the Cycladic Akrotiri town with 4000–5000 inhabitants [53] and the Gournia town with 4000 inhabitants (http://www.minoancrete.com/gournia.htm). There are some indications that the population of Crete was rising significantly around 1550–1500 BC [54]. Floods [13] describes groundwater levels in Eastern Crete that clearly indicate an advanced stage of drought occurring during this period. There is little doubt that irrigation systems were developed then, and the best-known example of this is what is called linies (the word linea = straight line), which was found in the Lassithi plateau (Figure 3). This conclusion follows from the Minoan settlements at Papoura, Kastelo, Plati, and in Karfi, and the famous caves at the sacred peak Kronion in the Trapeza region and Diktaion Andro. Here, numerous drainage systems and irrigation canals intersect and create a remarkable hydraulic work. More on the history of the Lassithi plateau can be found in the section on the Venetian period. Probably, Minyes transferred this technique later to Central Greece [55] to provide the basis for hydraulic works at the Lake Kopais. Generally speaking, irrigation and drainage technologies were further developed and extended to new regions during the Mycenaean era with a greater pace, leading to further technological and economic progress and contributing to the creation of the Classical civilization [52].

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

Figure 3. The Lassithi plateau: (**a**) a general view and (**b**) a drain (photos A. N. Angelakis).

The outputs of the central sewerage and drainage canals in Minoan palaces and cities, such as Knossos, Phaistos, and Malia, were quite similar. However, on the one hand, the disposal centers at the palaces of Knossos and Zakros were in the torrent Keratos and the sea, respectively [56]. On the other hand, sewage and rainwater from the palace of Phaistos and in the Villa at Agia Triada appears to have been discharged onto the farmlands located to the south of the palace and Villa, respectively [57].

2.4. Mycenaean Civilization (ca. 1900–1100 BC)

The drainage system of Kopais has also indicated considerable hydraulic works, which probably drained it during the late Mycenaean period (ca. 1450–1300 BC). Based on Strabo (IX 406–407, 414–415), the draining canals of Kopais were obtained by the Minyes and are considered descendants of Minoans as noted above [55]. The earthen dykes furnished by cyclopean walls were made at Lake Kopais, and three major canals with the dimensions of 40–50 km in length, and 40–80 m in width, and some walls up to 2–3 m thick traversed the previous lake area (Figure 4) [52].

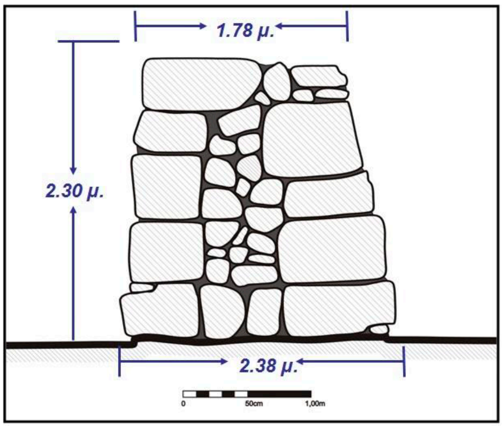

Figure 4. A schematic design of the dyke in Kopais [14].

2.5. Ancient Egypt (ca. 3000-67 BC)

For more than 5000 years, the people of Egypt built a civilization on the basis of the symbiosis of the land with the River Nile. Since the early stages of the Egyptian civilization, irrigation and drainage of agricultural land was common across the lower portions of the Delta, which were sometimes marshy. However, drainage systems were not necessary for the area to become livable [58].

Construction of dams along the Nile, separating the Nile into different basins, preceded the Old Kingdom (ca. 2660–2100 BC). The dikes were installed with the banks of the River Nile, and different basins supporting an area of 400–1700 ha were leveled [58].

2.6. Indus (Harappan) Civilizations (ca. 2600–1900 BC)

The Indus/Harappan Civilization belongs to the Bronze period. It flourished in the vast river plains. The manson rains were able to generate surpluses of sufficient agriculture production to support all people [59,60]. The Indus civilization created their settlements around the monsoon's areas, a climate pattern for which the bulk of annual precipitation is seen during four months. Huge rainfall and specific topography in the Indus valley were obstacles to maintaining main irrigation canals in this area. In the Baluchistan area, Indus settlements built diversion canal systems to direct floodwaters to their farms, and there is also some evidence of building small canals for irrigation in the area of Shortughai located in Northern Afghanistan [61].

3. Early Chinese Dynasties

3.1. Drainage in the Pre-Qin Period (21st Century BC—ca. 220 BC)

If irrigation is the means applied in the face of insufficient rainfall, drainage is the necessary engineering measure in the face of superfluous water yield. During the Xia and Shang dynasties (ca. 2000–1066 BC) the climate of the Huang-Huai-Hai plain in the springtime and autumn period was warmer than that of the present [62], and rainfall was more abundant. There were more bogs and lakes than today, and to change waterlogging bog areas into cultivatable agricultural regions, drainage should have been a necessary water conservancy measure. Allegedly, the main feature of Dayu's flood control was to dredge stagnant water and eliminate waterlogging [63]. Notice that Dayu was a legendary hero who contributed to flood control in ancient China and established the Xia Dynasty (ca. 21st century–16th century BC). These records of the Pre-Qin period indicated that drainage in the Northern Plain of China was a water conservancy measure, used more frequently by government forces than irrigation and flood control. The system of constructing water channels among fields expanded as the result of an intended policy of governing the country according to the principles of Confucianism and was the time-honored evidence that the origin of large-scale drainage engineering had a longer history than irrigation engineering in China.

3.2. Chunqiu Period (ca. 770–403 BC)

Field irrigation and drainage channel engineering was described explicitly by the philosopher Chuang Tse who lived during the Jin dynasty (1115–1234 AD) at the latest. Sima Biao (about 306 AD) made annotations on Mu and Quan in Chuang Tse: The land on the ridge is Mu and below the ridge is Quan. According to Sima Biao, the relative position of ditch and field indicated that "Quan" was field drainage engineering. Unlike gravity irrigated channels, Quan was the kind of subsurface ditch (channel) under the soil surface, and waterlogging in fields was discharged to ditches and then to rivers, constituting a multilevel drainage ditch channel system.

According to The Homely Talks of Confucius, when Zilu acted as the Prime Minister of State of Pu (belonging to the State of Wei in the Chunqiu Period, which corresponds to the northeast of present day Changyuan County, Henan), he was concerned by the threats caused by rainstorms and subsequent floods. Accordingly, he mobilized the masses to construct drainage ditches, and according to Confucius, he performed excellent. In The Warring States period (ca. 481–403 BC), Xun Kuang made comments on government responsibilities of the Sikong (magistrate): build an embankment, dredge the ditch, make a water channel to enable water to flow correctly, and build a reservoir to store water or discharge flood, so that people have farmlands to cultivate. These are the duty of the Sikong [64].

Clearly, the abovementioned projects were large-scale drainage systems which included embankments, beams, ditches, channels, and other engineering facilities. This also reflected that frequent large-scale drainage was extremely burdensome, and national political action was required for its implementation. Later, large-scale regional drainage projects were constructed in the Yellow River Basin. During the regime of Xining of the Northern Song dynasty, after diversion of the Yellow River, section runoff converged in Puzhou (presently north of Juancheng of Shandong), and Jizhou (presently

Juye of Shandong) to form a large-scale waterlogging lake. Wang Ziyuan, Tiju Changpingcang (magistrate) took charge of a large-scale water drainage project presumably in the 4th year of the regime of Xining (1071 AD) and recovered 4200 Qing (unit of area, equal to 6.6667 ha) of farmland to the east of Beijing.

During the pre-Qin dynasty, water channels between fields were made for regional drainage, and their shape and structure is described in the Book of Diverse Crafts—Craftsman [65]. These channels showed the same concept as is found in modern drainage channels: "the water channels flow from the branch to the mainstream and then to great rivers, and therefore sectional areas of water channels become larger."

4. Pre-Columbian Era (Maya and Inca) (ca. 2500 BC to 1540 AD)

The Prehispanic Maya lived and farmed in a region with few permanent water bodies, which was additionally marked by distinct wet and dry seasons (Figure 5).

Figure 5. Map of the Maya area [66].

Maya farmers had to predict the start of the rainy season and time the planting of their crops so that new seedlings would be sustained by the rainwater. Seasonal water bodies, such as aguadas (rain-fed depressions), bajos (wetlands), and swamps provided a natural water resource that disappeared by the end of the dry season, and as settlements grew in size, the Maya began to develop new ways of providing adequate water supplies. They constructed elaborate water management systems to capture, store, and redistribute water to support both urban life and large-scale agriculture. While most Mayan water management systems were constructed to face the problem of water scarcity, in the wetlands of Northern Belize, the Maya built ditches and canals that created arable land from the bajos [67].

In the wetlands of Northern Belize, the Maya faced a different problem than that of management of overflooding water. Maya farmers built a series of raised beds surrounded by canals, which enabled them to farm in swampy lands that provided fertile sediment and water for their crops, and aquatic animals to supplement their diet [68]. This system is reminiscent of the Aztec chinampas, though on a smaller scale.

As the Incan civilization emerged and flourished in ancient Peru between ca. 1400–1533 AD, they relied on agricultural production. This civilization not only enhanced various crops for feed and medicinal use but also thoroughly understood the planting of the soil, the correct methods of watering, and soil protection through means of terraces built at great expense, but mainly the art of proper drainage [69]. Some steep mountains and huge precipitation were overcome through the excellent ability of the Inca people to build perfect building foundations and installation of drainage canals since their establishment [70]. The drainage system built through the Inca people at Machu Picchu indicates a considerable public effort. The difficult site constraints related to approximately 2000 mm/year precipitation, landslides, steep slopes, and inaccessibility posed drainage system challenges managed by the Inca civilization (Figure 6). The drainage system at Machu Picchu reveals the secret of its longevity. Archaeologists and scientists have long overlooked this. In the lack of proper drainage and foundation building, there would not be much left of Emperor Pachacuti [70].

Figure 6. Machu Picchu Agricultural Terraces (by Hiram Bingham in 1912) showing tons of undamaged walls made by stone which resisted Llndslides and earthquakes. Drainage systems (surface and subsurface) were built to manage average annual rainfall of 1940 mm [69].

5. Historical Times

5.1. Archaic Through the Classical Greek Periods

The ancient Hellenes and Romans looked to the earliest times for the origin of water management: 'Wells were built by Danaus people who came from ancient Egypt into that part of ancient Greece called Argos Dipsion' that is, 'thirsting Argos' (Pliny, 7. 57). However, due to its distinct karst-fed water supply, the Argive plain became the landscape of 'hydromythology' par excellence in Ancient Greece [71,72]. In Homer's Odyssey, irrigation was a prominent feature of the gardens of Alcinous and Calypso (Homer, Od. 5.63–73; 7. 122–130; [73]), and in the 4th Century BC, Plato described an ambitious drainage system at legendary Atlantis:

"A trench was dug out to the depth of a plethron (1 plethron = 30.8 m) and to a uniform breadth of a stadion (1 stadion = 184.9 m), and since it was dug round the whole plain its length was around 10,000 stadia" (Critias 118D, transl. [74]).

These alleged origins of ancient Hellenic water management combining irrigation and drainage belong to the realms of the mythological past, and we must look to archaeological evidence and written evidence from more recent periods for safe historical documentation.

5.1.1. The Archaic Period

The development of the city constituted a vital element of society building in Hellenic antiquity from ca. 800–300 BC. In physical terms, the ancient Hellenic 'city-state' or polis comprised a physical infrastructure, which included houses for residence, city-walls, and sanctuaries, but also basic infrastructure such as roads, water supply, and drainage. Suitable locations for founding cities were chosen for their adequate water supply and preconditions for wastewater disposal [75]. Moreover, the physical outline of the polis included adjacent landscapes (chora) where citizen-farmers developed the dominant economic activity of agriculture. The successful outcome of urban development in Hellenic antiquity depended on continued access to agricultural resources—land, labor, and produce—and in that respect, know-how and practical water management remained central for the ancient Hellenic economy. Hence, as we shall see, the importance of water and drainage for farming to create and develop operational agricultural techniques and production also remained a central issue for the polis and its civic government.

Agricultural practices applied from the archaic period onwards explain why extensive climatic-induced devastation such as erosion was not prevailing. Farming was labor-intensive. A household (oikos) of four or five people, perhaps with additional slaves, did most of the work themselves on their small farm, and it has been claimed that efficiency on many farms were largely the result of an intensification of labor for drainage, irrigation, and terracing [76].

Dry-farming techniques, which aimed at maintaining moisture in the soil, remained the dominant form of cultivation in Hellenic antiquity [73], but new insight into a more diversified pallet of agricultural strategies and techniques has come to scholarly attention. Recent studies of ancient Greek Hellenic agriculture have pondered a gradual progression from small-scale intensive gardening in the archaic period to large-scale intensive agriculture partially fueled by irrigation [77]. There is, however, little evidence to support this as a gradual development and general trend. Contrary to this, some argue that gardening (primarily of kitchen gardens) and regular field cultivation, respectively, represented quite different modes of cultivation, concentration of resources such as manure and labor, and food production strategies [78,79]. In addition, scholars have maintained the existence of balanced modes of agropastoralism throughout antiquity (e.g., [80]), whereas intensive irrigation-based farming has been pondered more recently [77,79].

Throughout the Archaic period, it seems as if most agricultural activities took place in the plains circumscribing the main urban entities of the emerging poleis [81,82]. In addition, in the archaic period, agriculture expanded into the chora, and here, village communities and hamlets emerged [81,83].

Throughout the 6th and 5th centuries, a development surged towards integration of various parts of farmland, such as the rich plots of the plains and the so-called marginal land. Marginal land denoted tracts of land beyond or mixed in with the rich plots of the plains, often found in elevated ground on steep and wooded tracts. One hallmark of marginal land would have been the need for farmers to prepare and constantly maintain the tracts of eschatiai (literally: 'liminal land, land at the fringe or border') and phelleis ('stony ground') in order to uphold it as a profitable element for agricultural production [84]. Some suggest that intensive farming involving irrigation, drainage, and marginal land-eschatiai-was a distinct hallmark of farming from the 6th century onwards [85]. The literary evidence for an early date of eschatiai in Attica is, however, late (e.g., Aristotle, The Athenian Constitution, 16.6) and we lack facts on the ground to support this contention. Hence, we shall turn to the archaeological and epigraphic record from other parts of the Hellenic world for examples of early projects, which may have involved a significant element of drainage.

The work done in recent years on the chora of Metaponto and Herakleia in Magna Graecia [77,86] suggests that massive construction works were begun to facilitate the ambitious project of transforming marginal land into cultivable land of the plains. The work on the visible result of this endeavor the so-called 'division lines' has been dated to the period following the foundation of Metaponto in ca. 630—and it has been demonstrated that work on these combined drainage and irrigation structures continued until well into the Hellenistic period [77,86]. It is a distinct possibility that appliance of combined techniques of drainage and irrigation facilitated the transformation of substantial parts of Metaponto's territory from marginal, wet, and uncultivable land into arable 'land of the plains' suitable for agriculture. Thus, from an early date, Hellenes employed drainage to implement environmental change [79].

5.1.2. The Classical and the Hellenistic Periods

Agricultural development in the Classical period followed different strands in various parts of the Hellenic world. In Attica, exploitation of agricultural land in the plains had reached its carrying capacity before the democratic reforms of 508/7 BC, but expansion into the marginal tracts continued well into the century to follow. In Athens, the southernmost deme (county) of the peninsula farms were erected and hilly country was terraced, and this marginal land was protected against torrential rain by drainage channels and construction of basins for overflow [87].

The epigraphic record from Attica reveals widespread use of the marginal land category of *eschatia*, which should be understood as rough land often to be found in hilly country and transformed, e.g., by agricultural terraces and/or drainage facilities to prevent erosion [68,84,88–90]. Attica remained, however, a diverse peninsula comprising the rich and fertile plain of Marathon to the north and the northernmost demes at the Parnes mountain range. The area receives an average rainfall above 550 mm at sea-level, increasing by 100 mm for every 50 m gain in elevation, whereas Athens proper and its plain received around 400 mm annually [91]. Thus, it is plausible that the attraction associated with expansion into marginal elevated lands was to access lands having greater precipitation [92].

Athenians suffered from the erratic rainfall of the region. On the one hand, numerous food crises including shortage of locally grown grain called for massive import of grain; and the extant literary evidence documents fluctuating grain prices due to drought, war, etc. Evidence from the Athenian court rooms relates a couple of instances where local farmers felt the burden of the erratic weather, including one defendant in a forensic speech by Demosthenes (No. 55), who had to defend himself against the effects of allegedly unlawful diversion of torrential rain. A similar situation was perhaps anticipated in the Cretan polis of Gortyn, where farmers were instructed how to deal with run-off (IC IV 73 A, IC IV 52 A and 52 B, 1–6. [93,94]. Common to all of these examples are the concern for protection of property and most importantly agricultural crops and produce.

The sacred island of Delos saw early successful attempts of irrigation and drainage. From an early date, due to the island’s meagre water resources, the islanders developed capabilities to collect, store, and control water in the winter and divert it to fields in the growth season [79,95]. In addition, in Delos, drainage works were probably constructed in order to control the seasonal overflow of water from the islands limited karst-fed water reservoir [75], which presumably was redistributed among the numerous gardens of the island.

On implementation of public projects in ancient Greece, it was common practice to publicize the project specifications by erecting marble steles in some centers in which everybody would have known the details of the projectand, so it was difficult to breach the contract project. An interesting paradigm is the late Classical-early Hellenistic contract for draining and exploitation of the lake *Ptechae*, in Eretria in central Greece.

The Contractor of this effort was Chairephanes. Nevertheless, Chairephanes was not acting alone for the present case: The technical value of this facility necessitated a bigger joint venture [96].

The contract is written on a Pentelic marble stele (ca. 2nd half of the 4th century BC) and was discovered in Chalcis (1860). Presumably, the text written on the stele is the oldest complete contract of such a capitalistic construction scheme in history. It has long been in the Epigraphic Museum of Athens (EM11553) and is shown in Figure 7. The project called BOT (Build, Operate, and Transfer; the rather wordy construction contracts of present day) [97].

Figure 7. The inscription IG XII. 9. 191 A; EM11553, stipulating the conditions of the contract of the drainage project at Ptechai. The Epigraphic Museum of Athens [96].

The advantages of such a scheme are familiar to modern-day entrepreneurs: The owner, that is, the citizens of Eretria, does not pay anything in cash. The contractor is financing the execution of the works, and they offer their expertise to construct a technically perfect facility, as well as to operate it for an agreed period. The contractor, to cover their initial investment and their profit, receives all revenues. Subsequently, the facility is transferred to the owner, in an operational condition [96].

Surface relief sculptures indicate Gods being worshiped in the areas, including Apollo, Artemis, and Leto [98].

Finally, as mentioned above in the chapter on Mycenean drainage projects, the Kopais regions have had the attention of farmers and entrepreneurs from the earliest times in the Mycenean period to the present. In ca. the 1st century BC, Strabo in his Geography provides further information of the probable existence of hydraulic installations, with which the reclamation of land was achieved from Lake Kopais in the largest enclosed basin of Greece [99]. In the *Iliad*, Home describes the oldest known polders and related structures. They were found in the Periegesis of Pausanias, in which we can find a more detailed description on the hydraulic structures that concerned land reclamation. Specifically, the Pausanias description is as follows [100]: "Speaking at Orchomenus, I have already stated how the straight path leads to the Caphyes, first passes along the ravine, and afterwards left from the standing water, which I have spoken. Inside the dyke there is a place where the water comes in sufficient quantity to form a river that rushes soon into a chasm of earth, it rises again and afterwards, it is presented near Nases in a place called Rheunus. From there the water forms a river called Tragos of which the flow is not interrupted."

Moreover, among the several efforts to drain Kopais, an unfinished tunnel in the basin near to the sinkholes stands out from the Mycenaean era [99]. Further, from the Roman period, some other efforts of drainage in Kopais are reported [14].

5.2. Roman Period

The Roman author Cato wrote in ca. 200 BC extensively on farm drainage as practiced by Roman farmers. Later, Gaius Plinius Secundus (23–79 AD) described tile drainage that was used in the first century AD. The Romans were using open drains to remove ponded surface water and closed drains to remove surplus water from the soil itself [101]. The water was also channeled from water sources and distributed for the irrigation of some arable fields, orchards, vineyards, pastures, and gardens [102,103]. Irrigation channels could be in wood, stone, or dug into the ground. Romans also invented the Roman concrete (opus caementitium), which allowed the construction of long canals [104].

Romans exported to many regions their technical knowledge as well as their administrative rules, such as tax incentives, operations, and cadastral divisions linked to irrigation systems [105].

This spreading of knowledge was more prominent during the Roman Empire, which reached its largest expanse under Trajan (reigned 98–117 AD), encompassing an area of 5 million km^2 with an estimated population of 55–60 million inhabitants, accounting for between one-sixth and one-fourth of the world's total population. The territory of the Roman Empire in 117 AD is shown in Figure 8.

Figure 8. The map of Roman Empire-117 AD [106].

In the Italian peninsula, Romans used drains for irrigation of crops such as orchards, grass crops, vineyards, and olive groves and drain lines often represented the limits of the so-called *centuriation*, a method of land measurement [107].

Undoubtedly, "intensive agriculture" was developed in Britain during Roman rule. For instance, recently (2014), Cambridge University archaeologists found the earliest example of a Roman irrigation system in Britain, dating back to around 70 AD (Figure 9). It is believed that the discovered channels formed a network of ditches and ridges, which were used as a vineyard, or to grow asparagus.

Figure 9. Irrigation system in Roman civilization between 70 and 120 AD [108].

Piecemeal across the Roman Empire, irrigation canals were extended under severe weather conditions. Indeed, in North Africa and in the Eastern regions, Romans established permanent irrigation systems, which allowed agricultural exploitation of otherwise arid and unproductive territories [109]. In these provinces, the cultivation of grain was extended into the desert. For instance, in Libya, large areas were enclosed by terraced walls along the edges of the hills, which, at the end of the wadi, collected the silt from floodwaters. The land bounded by these terraces was fertilized, and the moist layer which was formed often resulted in very high crop returns.

The irrigation system in Iberia during Roman time was similar to that of the North African provinces.

The system of irrigated terraces and related Roman channels of irrigation played an important role in the economic life of the Jerusalem area. For instance, Figure 10 shows Roman irrigation channels and terraces, respectively, at Battir, a Palestinian village in the Bethlehem Governorate, located about eight kilometers to the southwest of Jerusalem.

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

Figure 10. Roman irrigation channel and terraces in Battir, a Palestinian village in the Bethlehem Governorate, located about 8 km to the southwest of Jerusalem: (**a**) irrigation channel and (**b**) terraces [110,111].

6. Modern Times

6.1. Chinese late Dynasties (ca. 1000–1911 AD)

Drainage and irrigation techniques were both important to agriculture in the plains, with a high underground water level and adjacent river estuary. A lot of land-based enclosures built in the riverside and coastal region of the Yangtze river and Pearl River Delta included hydraulic engineering integrating regional grading drainage of stagnant water, farm irrigation, land remediation, region navigation, and other functions, which were developed and improved constantly and subsequently became main water conservancy form in regions with frequent waterlogging including the lake region and riverside region [112–114]. The embankment of the Taihu Basin and a polder in the Dongting Lake were built during the Song dynasty (960–1276 AD). With an ever-increasing population pressure, polders were built to increase cultivated land. A schematic diagram of a Dike Paddy Field during the Qing dynasty is shown in Figure 11 [115,116].

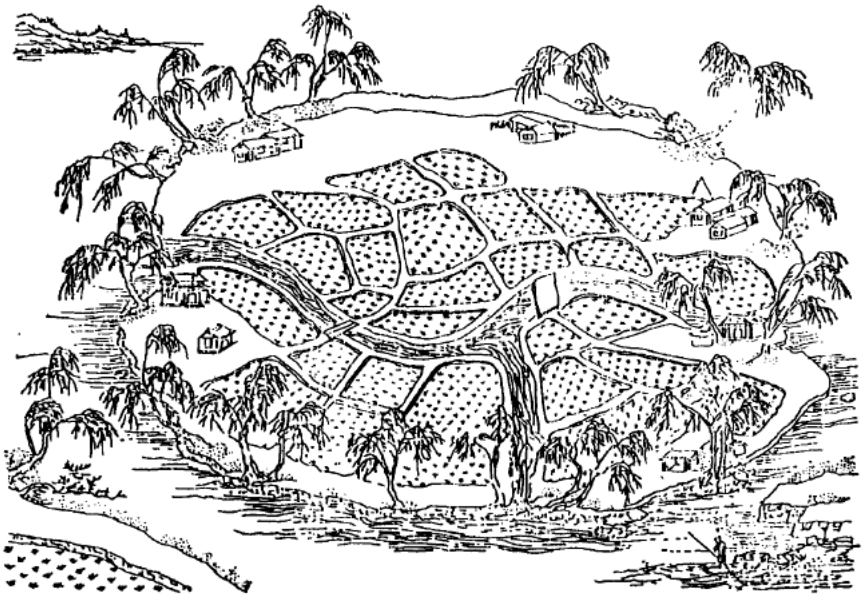

Figure 11. Schematic Diagram of Dike Paddy Fields (Source: *Shou Shi Tong Kao*, an agricultural book written by the government of the Qing dynasty, as reported by [116]).

6.2. The Ottoman Period (ca. mid 14th–1923 AD)

The emergence of the Ottoman civilization from the west of Turkey and their conquest of the Balkan lands commenced during the 14th century AD [117–119]. During that period, the sciences and especially those relevant to the agriculture remained almost unchanged.

6.3. India (19th and 20th Century)

In India, agriculture is the major sector in terms of its contribution to the overall economic growth of the country [120]. The first effort of drainage in India was seen in 1865, where the Punjab Government released some reports to deal with soil salinity. The reports highlighted that irrigation and drainage should be implemented simultaneously. However, the problems regarding soil salinity and waterlogging were not mentioned in the report until the next century (20th century). In 1928, The Royal Commission on Agriculture reported that drainage should be taken into account in all future irrigation projects. However, in practice, irrigation system projects were carried out without considering drainage canals even after Indian Independence Day in 1947. The 'Irrigation and drainage go together' parole was released by the Second Irrigation Commission (1972), the Government of India, and the National Commission on Agriculture (1976). There were some reasons why drainage was not an integrated element in 20th century irrigation projects such as that although the 'irrigation and drainage go together' principle was released, planners and farmers did not acknowledge the importance of drainage.

Although drainage projects remained at the agenda, it was not implemented until farmers had seen the problems of waterlogging and soil salinity in their farms [121,122].

7. Present Times (from 1900 to Today)

As the chapters above demonstrate, the practice of drainage of agricultural lands was known since prehistoric times but remained very limited until the second half of the 18th century when, as part of the rebirth of modern agriculture, improved drainage began to attract wider interest and application worldwide. As Stuyt et al. [123] pointed out, "In Europe, the initial drainage (subsurface) were built at the beginning of the Christian period. However, this kind of drainage (subsurface) was more or less forgotten in the next centuries."

The traditional drainpipes made from clay and concrete and drain envelopes made of organic materials or gravel were replaced by new drainage materials. The first clay drainpipe was used in England in 1810 [23], and a horseshoe-shaped tile was the first form of clay tile drainage used in England. Cylindrical drainage pipes were first manufactured in England in 1810 by the gardener John Reade at the village of Horsemenden in Kent. His handmade tiles were a great improvement over the old brush and stone drains and proved more popular than horseshoe drains [101].

Portland cement (concrete) was used to make drain tile for first time in 1830 [101]. Later on, in 1845, Tomas Scragg invented a machine for extruding clay tiles, which reduced their price by about 70% [124,125]. This led to an increase in their use [101]. In the 19th century, from England, the mechanical production of drainpipes spread over Europe and to the USA [19]. Concrete and clay pipes were used as field drainage systems until they practically became obsolete with the introduction of plastic pipes.

In the 1940s, rigid plastic and bituminous fiber pipes were introduced in the USA [126]. In the 1960s and 1970s, perforated plastic pipes with smooth walls were applied as subsurface drainage systems. Corrugated plastic pipes made of polyvinyl chloride (PVC) and polyethylene (PE) were extended during 1960s [127]. In the 1980s, corrugated PE and PVC pipes are considered to be the preferred standard, and the choice depended on the availability of the raw material and the price [127,128].

Many attempts and experiments were carried out in order to find suitable envelope materials, such as industrial waste products and fibers (e.g., coconut, glass rock wool) [129,130].

The evolution of drainage is the reason for the restraint of installation costs despite the sharply rising costs of labor and materials. Specifically, until the early 20th century, installation of drainage systems was done by individual farmers [103]. Thus, drain systems were designed and constructed based on the local experience and conditions, and later, suitable adjustments followed where it was considered necessary [131]. The invention of the trenching machines and specifically of the steam engine in the late 19th century contributed to the revolution of the drainage practices [4]. In 1890, diggers and trenchers driven by steam engines appeared [21], followed in 1906 by introduction of the dragline in the USA [22]. According to Zijlstra [132], drain installations were first mechanized in the USA around the 1920s. However, it was not in practice until the 1950s, and it was introduced in Europe in the early 1970s through the introduction of trenchless machines [128]. Secondly, most machines used for drainage systems worldwide are so-called "trenchers" [128].

The introduction of large-scale drainage systems began around the middle of the last century, when knowledge of drainage and salinity had acquired a solid theoretical basis. The theoretical development of the modern science of drainage may be considered to have started only 158 years ago in France under the direction of Henry Darcy, who conducted column experiments that established what has become known as Darcy's law [26].

Land reclamation and drainage received a scientific basis from around 1945 onwards. In 1940, Hooghoudt [133] presented his well-known analytical approach to the flow of groundwater to drains, and many other researchers, e.g., Ernst [134] and Kirkham [135], turned their attention to this field. Moreover, they confirmed, improved, and extended Hooghoudt's work and drainage formulae for steady and unsteady flow; and formulae for complicated multilayered aquifer systems were developed as well [131].

Until the 1970s, there was a great distance, figuratively and literally, between the engineer in the practical condition and the computer models in the office [131]. With the introduction of programmable pocket calculators and portable microcomputers which became available, as well as the appearance of user-friendly software, the situation rapidly changed from the 1980s onwards. All of these offered to every drainage engineer the opportunity to employ these powerful instruments in a direct interactive environment.

The increasing use of the computer modelsfor drainage design and the vast development of software drastically changed the traditional approach to engineering design. Specifically, computers were used for field surveys, data processing, groundwater modeling, drain spacing calculations, detailed design of drainage networks, including the preparation of maps, drawings, and cost estimates. In this way, computers made it possible to improve the speed and quality of drainage studies and designs. Moreover, the analysis of groundwater flow and the relative calculations of saltwater balance, which had previously been considered too complicated and too costly for manual execution, now became possible [131].

In the previous century, alternative drainage techniques developed, which have proven effective, affordable, socially acceptable, and environmentally friendly because they caused no degradation of natural land and water resources. One of them is biodrainage, which is defined as 'pumping of excess soil water using bio-energy through deep-rooted vegetation with high rate of transpiration' [136]. Interest in biodrainage is strong in Australia, China, India, Pakistan, the USA and some arid developing countries that see biodrainage as a low-cost option for combating waterlogging and salinization [137]. Further development of this interesting topic is beyond the framework of the present article.

At present, the performance of drainage systems is not only shown from a crop production aspect, but also from an environmental aspect, namely: (a) within the drained area, environmental interest focuses on the salinity and diversity of plant growth, and (b) downstream of the area drained, environmental issues because of the disposal of the drainage system are effluent.

In semi-arid regions of Western USA, subsurface drainage design and installation peaked in the 1960s–1970s and practically ended during the 1990s. There have been few, if any agricultural subsurface drainage system contractors in the valley regions since that time, though a few small contractors continue to operate in the coastal regions of the west. This roughly coincided with the final revision of the USBR Drainage Manual [138] that compiled applied research towards subsurface drainage system design from the previous three decades. Typically, in dry regions, agricultural subsurface drainage systems were designed primarily for the management of root zone salinity that accumulated from irrigation. With increasingly limited options for ultimate disposal of the often-saline subsurface drainage water, installation ceased, and research re-examined the water quality aspects of subsurface drainage system design [139–142]. These efforts suggested that drainage system design should consider installation and management methods directed at reducing subsurface drainage system flows and encouragement of crop water use of the shallow water table when and where possible. If combined irrigation–drainage system management was not possible, the collected subsurface drainage water could be used to irrigate progressively more salt-tolerant crops and finally dispose of them through evaporation from salt ponds or develop them as an alternative irrigation water supply [143]. Finally, while previously drained lands were fallowed due to lack of subsurface drainage water disposal options, and competition for limited water supplies persisted, research and efforts in California have been directed at developing subsurface drainage water as a possible water supply (e.g., [142,143]).

In summary, in the past 60 years, a rapid increase has been taken into account in installation methods and drainage materials (such as pipes and envelopes). Specifically, subsurface drainage techniques were modernized more through innovative studies and development from 1960 to 1975 than during the past century.

Considering the exponential population growth on the planet [144], the request for greater food and consequently the need for an agricultural drainage evolution should be considered [145].

During the last 30 years and particularly the 21st century, new topics such as best management practices (BMP) [146], smart drainage [147], automated drainage [148,149], and sustainable drainage [149,150] have been considered to address the challenges regarding climate change and environmental issues to meet sustainable development in future [151–157].

In the Appendix A, a timeline of the historical development of drainage of agricultural lands has been presented.

8. Discussion and Conclusions

The state-of-the-art holds that adequate drainage improves soil structure and increase and perpetuates the productivity of soils. For example, adequate drainage: (a) facilitates early plowing and planting; (b) lengthens the crop-growing season; (c) provides more available soil-water and nutrients by increasing the vadose-zone; (d) increases soil aeration; (e) decreases soil erosion and gullying by increasing soil filtration; (f) favors growth of soil microorganisms; (g) leaches excess salts from the soil; and (h) assures higher soil temperature.

The worst farmers cannot desolate agricultural land if there is a proper drainage system. In addition, the best farmers cannot help to improve the soil's condition if there is no proper drainage system. For instance, Adams [30] explained the collapse of Mesopotamian city-states in the 1st millennium BC as the outcome of episodic political catastrophes and absence/change/in the Mesopotamian alluvium deposits from Euphrates and Tigris. In this area, and especially in Khuzestan and Western Iraq [9,30], agricultural intensification and excessive irrigation without drainage systems led to reduced harvests, with developing prosperity, security, and stability. In the following years, though, the rise of saline groundwater eroded or destroyed agricultural productivity, and thus stability [158]. Whole civilizations had collapsed due to lack of drainage systems. Therefore, having information about challenges and opportunities of agricultural drainage systems is essential to prevent the mentioned problems and to achieve sustainable agricultural development in the future.

Irrigation and drainage of agricultural lands have been known in Egypt and Mesopotamia since ca. 5000 BC, when the water of the flooding Rivers Nile, Tigris, and Euphrates was diverted to the agricultural fields for a couple of months during the summer and autumn. The water was then drained into the river at the right moment in the growth cycle. Further, some archeological evidence suggests that pre-Columbian civilizations used subsurface drainage [12]. The first evidence of modern civilization and use of artificial water management (irrigation and drainage) was observed in Iran before ca. 4000 BC [6,32]. The other evidence belongs to Chogha Mish in Southwestern Iran (ca. 3400–2900 BC). In this region, drainage systems were formed of clay pipes and baked clay bricks [35–37].

In addition to the Mesopotamian civilizations, Minoans in Crete and an unknown civilization in the Indus valley (Harappans) appear to have used drainage techniques since the early Bronze Age [55]. These reclamation practices were further developed and extended in prehistorical times by the Mycenaean societies and thereafter to historical times.

The basic 'economy' of the Greek City-state (ca. 650–67 BC) rested on operational agricultural systems, which included techniques of drainage, irrigation, and terracing. Although dry-farming techniques remained dominant in various forms of cultivation, it has been suggested that intensive farming involving irrigation, drainage, and marginal land was a distinct hallmark of farming in some city-states from the 6th century onwards. It appears that massive drainage projects were begun at Metaponto in Magna Graecia, and projects were outlined at Eretria in the island of Euboea, and possibly also in the Aegean island of Delos. Further, marginal land in southernmost Attica was protected against torrential rain by drainage channels and construction of basins for overflow.

Romans contributed significantly to the advancement of water engineering and irrigation [46]. They had sophisticated knowledge of hydrology and introduced horticulture in their agriculture system. There has been evidence of gardens and wells, and planting beds arranged in parallel and along a slope. During dry periods, water would have been transferred from the wells into the ditches to irrigate crops. Romans greatly increased the scale of drainage projects, inventing concrete (opus caementitium) pipes and building much longer drainage canals. Intensive agriculture was developed in order to feed the increased population at that period. Thus, drainage technology was extended to the Italian peninsula, to Britain, to North African regions, to Palestine, and elsewhere.

Recently, Valipour [159] studied major problems and perspectives of drainage vs. waterlogging and salinity throughout the world. Compared to waterlogging, the rate of salinity problems was severely higher, and more research needs to be done in order to meet the challenges associated with this problem (Figure 12). In India, although less than 10% of the cultivated areas have been equipped with drainage systems, 23% of studies on drainage originate from this country from 1972 to 2013. This volume of investigations has had two achievements: first, prevention of salinity, and second, reduction of waterlogging (more than 70%) in Indian agriculture; and similar results were demonstrated in

Australia, the USA, and Pakistan. This shows clearly the need for more research on the relationship between drainage and irrigation systems in various regions of the world [159].

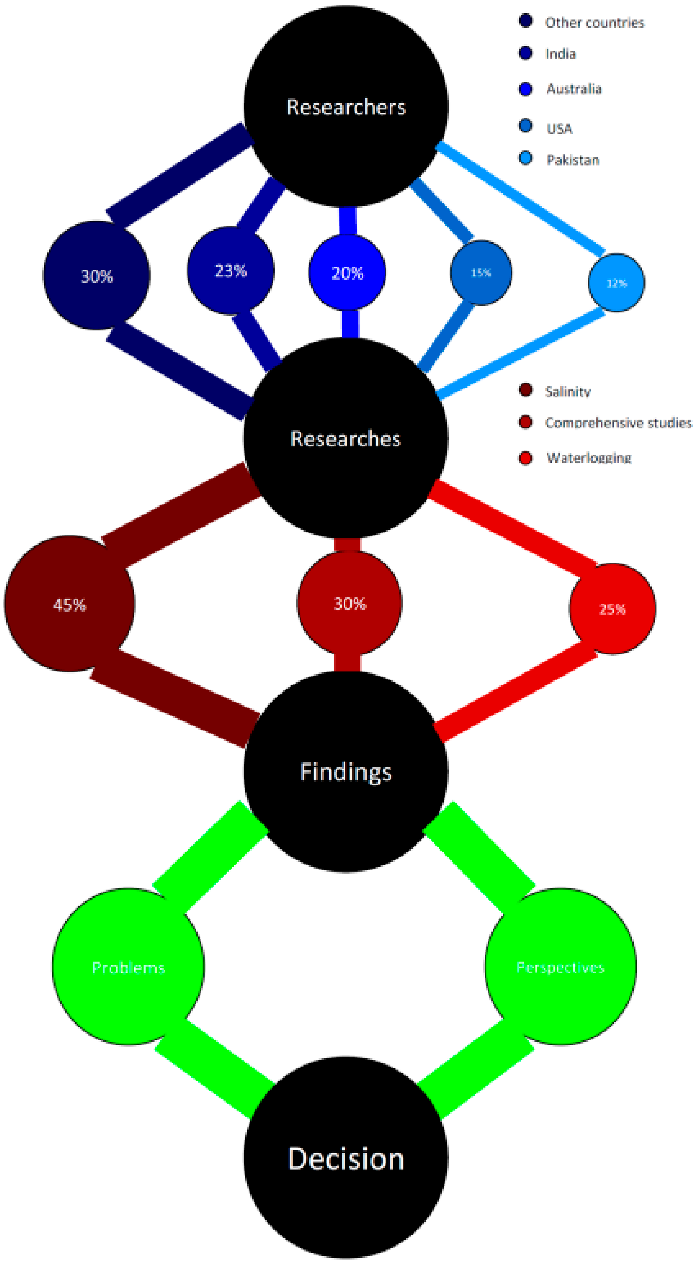

Figure 12. A schematic diagram showing different aspects of drainage studies in the world [159].

Wichelns and Qadir [160] stated that we can start to decrease the degree to which waterlogging and soil salinity impair productivity and decrease crop production by designing and implementing effective local solutions [160].

The need of drainage in India was recognized in 1865 when initial reports on soil salinity appeared. In arid and semi-arid areas, salinity also develops as a result of increasing watertables, and undoubtedly, installation of subsurface drainage systems improving the aeration of root zones will further improve the quality of soil. In Eastern Rajasthan Upland, in India, hydraulic conductivity using filter was detected to be the highest, and entrance resistance was the lowest [161].

In China, in the fifth year of Emperor Xianfeng's reign of the Qing dynasty (1855), after re-channeling the Yellow River at Tongwaxiang of Henan to flow towards the north, downstream of the Huaihe River, it converged at the Yangtze River and flowed into the sea after passing through Lake Hongzel, causing even more serious waterlogging in the Lixia Lake Area at the east of Lake Hongzel. From 1914 to 1920, the first dredging planning of the Huaihe River of modern water conservancy in the charge of Zhang Jian, the Director of National Bureau of Water Conservancy, coincided with the thought of the Huainan drainage engineering system of Qiu Jun in the Ming dynasty to a certain extent. The main difference lay in that the engineering design of the latter is established on the basis of quantitative analysis of modern river hydrological parameters, such as flow and flow rate [162].

At present, engineers typically consider a design period of hydrostructures of approximately 40–50 years, which is accossiated with economic and environmental considerations. It is difficult to infer the design principles of ancient people. Nevertheless, it is notable that several ancient hydraulic works, such as drainage systems, have operated for very long periods, sometimes until contemporary times. For example, the drainage system in the Lasithi plateau in the island of Crete has been in operation since the Venetian and probably since the Minoan times. There are also some investigations claiming that agricultural methods and particularly drainage systems employed in prehistoric times have a potential to serve as models for sustainable agriculture today [163].

Application of drainage systems, particularly subsurface systems, as an intervention to reclaim the lands with the problem of waterlogging and/or salinity and to achieve sustainability of irrigated agriculture has been known since ancient times. The subsurface drainage systems could be evaluated based on hydraulic properties of enveloped materials, various drainage characteristics of soil, and assessment of drainage spacing equations for the disposal of effluent material. The evolution of agricultural land drainage methods through the past centuries up to the present could act as a guideline or to operationalize the drainage systems/canals in an effective and eco-friendly manner, and this could be applied in the future.

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Appendix A

Table A1. Timeline for historical development of drainage of agricultural lands.

8000–4000 BC	The First Symbols of the Modern Civilization and Irrigated Agriculture was Visible in Iran.
5220–4990 BC	Use of water channel for irrigation and drainage in Tepe Pardis, Iran.
4500 BC	Irrigation and drainage were extended in the Indus era.
4000–3000 BC	Initial applications of water power was applied for irrigation porpuses in Mesopotamia.
3000 BC	Sophisticated water storage and irrigation canals were developed by the Indus civilization.
2500–2000 BC	Preliminary drainage practices were used by Minoan and Indus valley civilizations.
2000 BC	The first clay pipes were usedin Babylonia.
2000–1200 BC	Use of drainpipes in the lower Indus valley and bamboo pipes as drains (biodrainage) in China.
1200 BC	Use of qanat for the first time to irrigate and drain in Kerman, Iran.
900–800 BC	Desert agriculture and poor drainage using hillside runoff during the Israelite Period at the time of the Judean Kings.

Table A2. Timeline for historical development of drainage of agricultural lands.

400 BC	Egyptians and Greeks drained land using a system of surface ditches to drain individual areas.
287–212 BC	Archimedes the famous Syracusan [164].
200 BC	Marcus Porcius Cato (23–194 BC) described the use of brush, straw, poles, stones, boards and tile to drain fields.
200 BC–700 AD	Irrigation and drainage based on the utilization of surface runoff from the meager winter storms was developed to a high technical degree, reaching its peak during the Nabatean–Roman–Byzantine domination of the Central Negev desert.
900 AD	One can trace the ancient irrigation canals out of the Salt river in Arizona, near present day Phoenix. These canals were built by the Hohokam Indians in about 900 AD. Hohokam Indians were built irrigation canals out of the Salt river in Arizona, near present-day Phoenix.
1252	In the 12th, century, Thomas Backet continued the drainage techniques of Romans. In 1252, this has a great significance as Henry III confirmed the Charter of Romney Marsh.
1738	Ural hydraulic machinery plant established.
1790	Plenty Ltd established.
1800	The birth of a hydraulic society on the Midwestern frontier of the United States due to drainage on the Grand Prairie.
1810	Cylindrical drainage pipes were first manufactured in England by John Reade, a gardener at Horsemenden.
1830	Portland cement was first used to make a drain tile.
1835	Tile drainage was first introduced to the USA by J. Johnston, known as the "Father of American Tile Drainage", introduced handmade drain tiles on his farm.
1838	Benjamin Wharten produced the first American-made tile using Scottish tiles (bought by Johnston) as his patterns).
1846	Land drainage recognized as a national asset (e.g., Russia)
1862	David Ogden developed a machine for making drainpipes from cement and sand.
1894	James B. Hill (1856–1945) devised a machine that he later named the Buckeye Traction Ditcher (U.S. Patent 523–790; 31 July 1898).
1907	James B. Hill (1856–1945) designed wheels that could travel over soft, wet earth.
1920	Installation of drainage systems was mechanized in the USA.
1940–1965	Presenting the main formulae to determine spacing of drains.
1950	Introduction of mechanized installation of the drains in Europe.
1959	The first experiments with thin-walled smooth plastic pipes started.
1960	Leap forward occurred with the introduction of corrugated plastic tubing installed with laser-beam controlled high-speed trenchers or drain plows.
1967	The smooth-walled plastic pipe has gradually been replaced by corrugated PVC pipes.
1970's (late)	There came into practice the application of drainage theory in the form of computerized design methods and models.
1980	Package and practice for reclamation of waterlogged and saline soil in India.
1984	Subsurface tile drainage was installed in India under the Indo-Dutch project.
1988	American Society of Mechanical Engineers designated an original Buckeye Steam traction Ditcher as an International Historic Mechanical Engineering Landmark.
21st Century	New topics on best management practices (BMP), smart drainage, automated drainage, and sustainable drainage have been considered to address the challenges regarding climate change and environmental issues.

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