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Review

Sustainability of Water, Sanitation, and Hygiene: From Prehistoric Times to the Present Times and the Future

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Citation: Angelakis, A.N.; Capodaglio, A.G.; Passchier, C.W.; Valipour, M.; Krasilnikoff, J.; Tzanakakis, V.A.; Sürmelihindi, G.; Baba, A.; Kumar, R.; Haut, B.; et al. Sustainability of Water, Sanitation, and Hygiene: From Prehistoric Times to the Present Times and the Future. *Water* **2023**, *15*, 1614. https://doi.org/10.3390/w15081614

Academic Editor: Qiting Zuo

Received: 27 March 2023
Revised: 15 April 2023
Accepted: 16 April 2023
Published: 20 April 2023

Abstract: Contaminated water and poor sanitation are associated with disease transmission. Absent, inadequate, or improperly managed water resources and sanitation systems expose individuals to preventable health risks. Billions of people lack access to these basic services today and will remain in this condition for decades to come. As we are usually thinking and talking about water, sanitation and hygiene services have changed. Looking back at the history of water, sanitation, and hygiene can help us understand the challenges and opportunities of these issues and draw lessons to achieve sustainable development in the future. Throughout history, civilizations have successfully experimented with treating water and using it for drinking, sanitation, and agriculture. For example, the Minoan civilizations originally focused on water treatment and cleaning to improve the aesthetic properties of drinking water. During prehistoric times, Minoan and Indus Valley civilizations, dating back to about 2000 BC, were the first to focus on the treatment of water supplies. From the early Minoan period, they relied on rainwater collection. During historic times, Hippocrates was the first to invent and used a water filter in the form of a cloth bag, at about 400 BC, known today as the Hippocrates Sleeve. The Romans perfected existing water technologies on a larger scale and initiated their spread throughout the Empire. Hygiene in ancient Rome was promoted by the famous public baths and toilets, which were supplied with water through widely branched aqueducts that had a high standard of cleanliness for the time and were regularly maintained.

Keywords: prehistoric and historical times; middle and contemporary times; emerging trends; water supply pretreatment; water quality; toilets; WASH; sustainable development

1. Prolegomena

Water contributes much toward health.

Hippocrates (ca 460–370 BC), the famous ancient physician.

The history of water is equivalent to the history of the world and the history of water quality is equivalent to the history of life quality.

Andreas N. Angelakis.

This paper is dedicated to World Water Day. World Water Day is celebrated every year on March 22 by the United Nations (UN) to highlight the importance of fresh water. The day is used to advocate for the sustainable management of freshwater resources [1]. The annual theme focuses on issues relevant to clean water, sanitation, and hygiene (WASH), which is in line with the Sustainable Development Goal 6 targets [2]. However, we also address the history of water, in the spirit of Confucius (551–479 BC), who said: study the past before planning anything for the future.

Hygiene is a practice related to health and medicine. In medicine and everyday life, hygiene practices are employed as preventive measures to reduce the incidence and spreading of germs leading to disease [3]. In addition, WASH is crucial to human health and well-being. Contaminated water and poor sanitation are linked to the transmission of diseases such as cholera, dysentery, hepatitis A, typhoid, and polio, among the most common diseases. In addition, diarrhea symptoms are very common, happening in most people a few times each year. In most cases, the cause is unknown and it goes away on its own after a few days. However, dehydration is a dangerous side effect of diarrhea. Absent, inadequate, or inappropriately managed water and sanitation services expose individuals to preventable health risks. Billions of people today lack access to these basic services and will be in the same condition for decades, save for a rapid acceleration in the sector's progress. It was estimated that to reach universal access to drinking water, sanitation, and hygiene by 2030, as foreseen by the UN's Sustainable Development Goals (SDGs), the current rates of progress would need to increase fourfold. Such an achievement could save an estimated 829,000 people annually, who currently die from diseases directly attributable to unsafe water, inadequate sanitation, and poor hygiene practices [1]. Safe WASH is not only a prerequisite to health but contributes to livelihood, school attendance, and dignity and helps to create resilient communities living in healthy environments. Improper or inadequate management of urban, industrial, and agricultural wastewater means that drinking water may become dangerously contaminated, either bacteriologically or chemically. The natural or anthropically-driven presence of chemicals, particularly in groundwater (e.g., arsenic, fluoride, lead, and nitrates), can also induce severely adverse health effects.

Diarrhea symptoms are the most widespread linked to contaminated water, but other hazards are not uncommon. In 2017, over 220 million people required prophylaxis for schistosomiasis, a disease caused by parasitic worms contracted through exposure to infested water, with both acute and chronic effects [1].

Rosenqvist et al. [4] studied the transformation from technology to the practical systems by reviewing more than 200 literature publications from 1970 to 2015 on WASH. Finally, seven prevalent perspectives on sanitation services provision were analyzed and it was concluded: (a) sanitation services is a basic need of humans; (b) through appropriate technology, increasing services are covered; (c) the emergence of community management and, of course, participation; (d) there is an interest in participation by the private-sector; (f) the sanitation crisis was considered as a crisis of governance; and (g) sanitation is considered an inherently political practice and is currently focusing on sustainable sanitary systems. These seven perspectives provide a very useful conceptual framework that can provide basic guidance to researchers, academics, practitioners, and, of course, policy makers as they consider how to achieve the goal of sustainable development in the water and sanitation Sustainable Development Goal by 2030.

India is a good example of why WASH is significant in urbanizing areas under low water availability. More than half of the population of India, one of the most densely populated nations in the world, lives in suburban areas. People in India have limited access to sanitation and hygiene due to the country's rapid population expansion and limited availability of water. The majority of children's diarrhea-related deaths in India are caused by nearly half of the population who inhabit outskirts, polluting and contaminating the water. Due to unhygienic conditions and tainted water, 117,000 children under the age of five die each year from diarrhea [5]. According to research, little over half of Indians wash their hands after defecating. Fewer than 40% of Indian people wash their hands before handling food, and just 30% wash their hands before eating. However, using soap to wash hands might lessen the likelihood of developing respiratory infections and diarrheal diseases, which are most common in young children. Since about 600 million people do not use toilets, there is a greater chance of water contamination and diarrhea since their waste penetrates the environment. Children with diarrhea are more vulnerable to pneumonia and other ailments like malnutrition, which affects almost 50% of children. Only about 10% of rural homes correctly dispose of their garbage, with the majority being either dumped in the trash or left outside [5]. Approximately 6% of young children under the age of five use toilets.

Khuller [6], reported that a report titled "Composite Water Management Index (CWMI)", published by in June 2018, indicated that India is experiencing the worst water crisis in its history; that nearly 600 million people face high to extreme water stress; and that about 200,000 people die each year due to inadequate access to clean water. By 2030, the study found, the amount of water needed will be roughly equal to the amount available. In 2014, Indian Prime Minister Narendra Modi started promoting increased cleanliness initiatives by October 2019. Since he stated this goal, there has been a tremendous improvement in the accessibility of utilities like clean water and hygiene. In 2013, there were 550 million individuals living in agricultural areas, while in 2014, there were 320 million less. Overall, access to clean water for drinking and proper sewage disposal has increased from 39% in October 2014 to over 90% in August 2018 [5].

This is a review paper that is organized into six sections, all including geographical and chronological developments as well as observations on various types of WASH technologies and practices employed: Section 1 Prolegomena is an introduction to WASH. Section 2 describes the distinct histories of WASH from the prehistoric to the Medieval times. The following Section 3 deals with WASH in the Early and Mid-Modern times, and Section 4 discusses WASH in contemporary times. Section 5 deals with emerging trends and possible future challenges of WASH measures development. Finally, Section 6, i.e., the Epilogue, deals with conclusions and highlights.

2. WASH: From Prehistoric Era to Medieval Era (ca 7600 BC–1400 AD)

2.1. Prehistoric Period (ca 7600–1100 BC)

2.1.1. Iranian and Other Prehistoric Civilizations (ca 7600–1100 BC)

Perhaps few people know that the Iranians had constructed one of the first baths in the palace of Persepolis, which was probably constructed by Persia's King about 3000 years ago. One of the most important components of Iranian architecture is Persian Hammams, since the ancient time. At that time, the public bathrooms in Iran were not just used for health purposes but were considered important places for public discussion and decisions, forming cultural circles and enhancing local folklore [7].

During that time, public bathrooms were dominant everywhere in Iran, and people went to the bathroom for cleaning purposes at least once a week. Men went usually to the bath early in the morning, before sunrise until eight o'clock, and women used to go to the bath from that hour until noon and sometimes several hours in the afternoon. Even today, a limited number of public baths still exist in most areas of Iran. Traditions and customs have been adhered to in ancient times, and some have found the proverbial aspect. One of the rituals took place when everyone entered the bathroom, they would take a large bucket or smaller one of warm water from the bath treasury to express politeness and humility to the older people sitting in the bathroom, offering bagging and soap. This was done by Iranian people in their baths. In addition, when Persian people entered the courtyard of their bath, they poured hot/warm water over their bodies/heads for cleaning purposes [7].

2.1.2. Minoan and Mycenaean Civilizations (ca 3200–1100 BC)

In the Minoan Age (ca 3200–1100 BC), there is no relevant information that indicates the Minoans were aware of human illness, specifically to its causes. During that time, the knowledge of human illness was based on theocratic beliefs. According the Hellenic mythology, the meaning and spirit of the Minoan Goddess of the Snake took on many different meanings [8]. For example, the snake had a protective role, by which the chthonic (underworld) power of the Goddess of Earth was represented [9]. On the other hand, the snake could have a negative role too as a cause of death and an avenger of mythical creatures [10]. The Minoan Snake Goddess statue from Knossos palace was originally identified by Evans [11] and is shown in Figure 1a. At that time, matriarchy was dominant, even in theocratic regime; no male god has been identified.

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

Figure 1. Minoan goddess and offerings to the gods: (**a**) Snake Goddess; (**b**) offerings to the gods for healing were mainly relevant to the body parts (Photos Andreas N. Angelakis from the Museum of History of Medicine, University of Crete, Iraklion, Greece).

The female presence was very important, almost dominant, in the Minoan era. It acquired divine and sovereign qualities, with women enjoying a prominent position in Minoan society [12]. Additionally, the identification of women with the earthly element and the blessing of human reproduction, as well as with the reproductive forces of nature, was the essential foundation for the theory of matriarchy.

During the Minoan times, the offerings (votives) were, in practice, an ancient custom. For healing purposes, the offerings to the gods were mainly relevant to the body parts (Figure 1b). Additionally, there were sacrificial offerings, such as burning, smashing, killing, etc. [8].

Minoans originally treated potable water in order to improve the aesthetic characteristics. The prehistoric Minoans and Indus Valley civilizations were the first to develop water supply treatment technologies at about 2000 BC. Minoans relied on rainwater collecting and harvesting, (e.g., in Trypiti and Chamaize in the eastern part of the island of Crete), since their early time. These hydro-technologies were further improved in the Neopalatial period (ca 1650–1450 BC), when, in several Cretan settlements (e.g., Knossos, Phaistos, Agia Triada, Pyrgos Myrtou, and Fournou Korifi), water supply was dependent on rainfall [13]. In these places, rainwater was collected by runoff water from cleaning opened surfaces (e.g., yards and roofs) and treated through sandy filters [14] before it reached the cisterns (Figure 2a).

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

Figure 2. Water supply pretreatment: (**a**) Special cistern with a coarse sandy filter in Phaistos and (**b**) small stone-made sedimentation tank for suspended particles to settle out in Tylissos (Photos Andreas N. Angelakis).

Moreover, to remove suspended solids from the water as sediment, small sedimentation tanks were used before the water was stored in a cistern (e.g., in Tylissos, shown in Figure 2b).

In addition, in Minoan towns and palaces, sanitation was very well managed. They had toilets and sewage and drainage systems were carefully planned. No public toilets were known in Minoan Crete, while in several houses, the lavatory was located in private living rooms (e.g., Knossos, Phaistos, Tylissos, Malia, and Gournia). In most cases, evidence for the identification of a toilet was from the existence of a sewer at the floor level passing through the exterior wall and connecting with the outside central sewerage and drainage system [15]. The toilet in the residential quarter of the Palace of Minos in Knossos is probably the earliest flush lavatory in the Mediterranean region identified to date [16] (Figure 3a).

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

Figure 3. Minoan sanitation: (**a**) A general view of the ground-floor toilet in the residential quarter of the palace of Knossos and (**b**) part of the Minoan drainage system at the "Little palace" at Knossos (with permission of A. N. Angelakis).

In many towns, well-developed sewerage and drainage systems were developed to carry away sewage and rainwater, including storm waters. Minoan palaces and towns were equipped with elaborate storm drainage and sewerage systems (Figure 3b). For example, in Knossos palace, it is clearly shown how rainwater was drained from the roof through light wells and used to flush out sewage from bathrooms and lavatories [17]. All palaces had applied strategies to dispose of wastewater [18].

One of the most advanced Minoan sanitary and storm sewer systems was discovered in Hagia Triada (close to the south coast of Crete, a few kms west of Phaistos). The Italian writer Angelo Mosso [19], who visited Phaistos and the villa of Hagia Triada at the beginning of the 20th century and inspected the storm sewer system, noticed that all the sewers of the villa functioned perfectly and stated:

> *" . . . all the sewers were still working! It was very interesting for me to see the water in the drainages and sewers so big that a man could enter. I doubt if there are other examples of ancient sewerages working after 4 thousand years . . . "*

Additionally, Gray [20], who related this story and quoted Mosso, added the following statement:

> *Perhaps we also may be permitted to doubt whether our modern sewerage systems will still be functioning after even one thousand years.*

2.1.3. Indus Valley Civilizations (ca 3200–1300 BC)

The Indus Valley Civilization, which existed in what is now Pakistan and northwest India between approximately 3300 and 1300 BC, is considered to have had some of the most advanced sanitation systems of the ancient world. Ancient Indians, as well as people from other civilizations and other historical eras, were greatly impacted by the use of toilets. The Indus Civilization was well known for its hydraulic engineering and produced numerous ground-breaking water supply and sanitation systems. They also had the world's oldest flush toilet system; some courtyard residences had a washing platform as well as a hole for the toilet's waste disposal. Using a clay brick pipe and a shared brick drain that fed into an adjacent soak pit, water from the house's central well would be used to flush the toilet hole [21]. Excavations of the civilization's cities have revealed a sophisticated network of brick-lined drains and advanced toilets that were connected to these drains.

The Indus Valley people used a system of underground brick-lined drains that ran alongside the streets and into homes. Inside the homes, toilets were built over the drains, which allowed for the easy disposal of waste. These toilets were simple holes in the ground that were covered with a brick slab and had a small channel leading to the drain below. The toilets were connected to the homes' water supply, which would have been used to flush the toilets. This advanced sanitation system was not only a practical solution for waste disposal, but it also likely had significant public health benefits [5].

The Indus Valley Civilization's sanitation system was designed to prevent the spread of disease by keeping waste separate from living areas and by ensuring that waste was quickly and efficiently removed from the cities. In contrast, in ancient civilizations of Egypt and Mesopotamia, toilets were not widely used and instead, people would just defecate in the streets or open cesspits. As long as the Indus Valley Civilization, which had developed in and around Harappa and Mohenjo-Daro, existed, toilets had existed in India. The homes' waste water was channeled into a sophisticated municipal sewage system [22].

In addition, pipes were installed on the roofs of the homes to channel rainwater into the sewage system, which also served as the location for the toilets. Water could be drained through terra-cotta pipes in the walls, and in certain cases, a cradle for sitting in the toilet was provided. The sewage was subsequently sent into cesspools, which were constructed at the junction of two drains with rain running to them for routine maintenance. Nearly all of the dwellings from Harappa and Mohenjo-Daro had private bathrooms on the ground floor (Figure 4). There is evidence of the usage of water-borne toilets in the Indus Valley Civilization's archaeological remnants. In the year 2500 BC, at a location named Lothal in western India, which is 62 km from the city of Ahmedabad, the residents had water-borne toilets in every home which were connected by sewers that were lined with burned clay bricks [23]. It had manhole covers, chambers, and other features to make operations and maintenance easier. It represented the pinnacle of sanitary engineering. However, sanitary engineering science vanished from India with the collapse of the Indus Valley Civilization. After that, India's latrines remained rudimentary and open defecation spread like wildfire [24].

Figure 4. Flush and squat toilet in Mahenjedaro [24].

2.2. Historical Times (ca 1100 BC–476 AD)

2.2.1. Iron Age (ca 1200–750 BC)

It is known from Homer's epics, both the Iliad and the Odyssey, that the period to which Homer refers, i.e., the time of the Trojan War, covers the later Mycenaean or Late Helladic era (ca 12th century BC). In addition, these two epics also contain elements from the time of Homer (ca 8th century BC). During this period, WASH was fundamentally "religious", with Apollo having a central position.

2.2.2. Archaic, Classical, and Hellenistic Periods (ca 750–31 BC)

During the Archaic period (ca. 750–500 BC), urban centers of Greek city-states developed distinct features, which included water management structures, such as fountains, aqueducts, and measures, to facilitate drainage and the negative effects of erratic weather occurrences. In the absence of adequate natural water courses, some city-states constructed cisterns to ensure the supply of household requirements, including personal hygiene (on cisterns, see [25]). Later, in the Classical period (ca. 500–323 BC), public baths and bathrooms emerged in some larger city-states, such as Athens and Corinth. In addition, bathing developed in public contexts, such as the gymnasium and sanctuaries ([26], overview and introduction; Wassenhoven [24] on the classification of Baths and architecture).

Bathing culture developed in different directions throughout the Greek world. Facilities for bathing—designated rooms and bathtubs—have been identified in the palaces of Knossos and Phaistos, Crete, and at Mycenae and Tiryns on the Greek mainland ([27], but see now [28]).

Bathing rooms and bathtubs have been found in Bronze Age palace complexes, and tubs appear again in Ionia as early as the 7th century BC [29]. Bath houses (balaneia) are known from 5th and 4th century Athens, where the comic play writer Aristophanes and Xenophon referred to bathing (Symposium, 1.7) and the orator Isaeus (speeches 5 and 6) referred to bathhouses. It has recently been suggested that Greek bathing culture originated in Athens and later spread to the Greek world, including the cities of Corinth, and to the West at Kolophon in Ionia, Marseille, and Sicily, and later to North Africa and Egypt [26,30,31]. Athenian bath houses are documented archaeologically from the second half of the 5th century BC, but relatively few examples from the Greek mainland predate the Hellenistic period. From its very beginning, bathing houses were designed to meet local requirements, thus, for example, the inclusion of bathing at the facilities was supervised by the balaneus, to whom the guests paid a small fee. Thereafter, the balaneus assisted with trimming and supplied soap consisting of carbonate of soda (Nitre) and inferior oil. Normally, the guest had access to common tanks and bathtubs for more particular bathing [27]. Public bathing also took place in sanctuaries, but it remains a matter of scholarly dispute whether water management was solely connected to activities associated with cults and rituals or whether (some) sanctuaries offered more worldly services, such as bathing (discussion of these matters).

Undoubtedly, the Romans met with Greek bathing culture when they subdued Greece and Asia Minor in the 2nd century BC; but it remains a question to what extent the Romans borrowed bathing concepts (apart from the word balineum) from the Greeks, and thus, to what extent their further developments of the concept were original. Recent studies suggest, however, that the Romans also met with Greek bathing culture when they subdued the Greek city-states of Sicily and southern Italy in the 3rd through 2nd century BC [26]. Undoubtedly, bathing became more advanced in the Hellenistic period, and the innovation of baths contributed profoundly to architectural advancements of the central Mediterranean and Rome.

Alcmaeon of Croton, presumably trained by Pythagoras (ca 570–495 BC), was the first physician and physiologist in pre-Hippocratic medicine to ponder the possibility that water quality affected human health (Aëtius, *Opinion of the philosophers* V. 30.1) [8]. However, Hippocrates (ca 460–370 BC), one of the fathers of modern Western medicine, introduced empiric principles in strategies for treatments of somatic diseases and developed diets and regimens and made extensive use of herbs for therapeutic purposes. In a series of his books, Hippocrates mentions 236 herbal medicines.

Hippocrates is also accredited for the invention around 400 BC of a water filtering system, consisting of a cloth filter named Hippocrates' Sleeve (Figure 5). The primary function of the filter aimed at removing impurities from water, which was boiled beforehand, and thus suitable for medical procedures, cures, and treatments. The filter consisted of cloth, folded at the corners and suspended on a frame with jars underneath to collect the filtered water [8]. Ostensibly, Hippocrates' awareness of the importance of water's condition for human health was pivotal to his medical thinking.

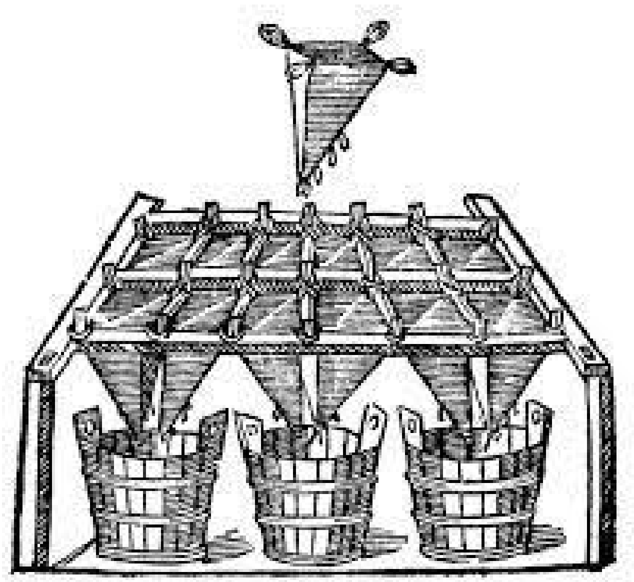

Figure 5. A brief history of the evolution of water [32].

In the course of the Classical and Hellenistic periods, citizens of the city-states founded several sanctuaries for healer Gods, including Asclepius and the local hero Amphiaraus of Oropus, north of Athens and Northern Attica. The remote location of many of these sanctuaries was probably associated with their unique nature and topography, which, undoubtedly, contributed to their healing nature. Asclepius' sanctuaries known as *Asclepieia* or *Asclepieions* were readily associated with places of healing and what one may describe as early forms of hospitals [33]. According to Angelakis et al. [8], from the 5th century onwards, more than 400 *Asclepieia* functioned at some point or the other across the ancient world, offering wide ranges of cures to whoever approached the God for advice and treatment [34]. Throughout the Classical period, the healer God's popularity increased, which is reflected in the fact that most Greek city-states had an *Asclepieion* [8]. Often, Asclepius was worshiped together with Artemis, who had healing powers, especially those needed for curing women diseases, including those associated with child birth [35]. In these contexts, water and cleanliness was at the heart of medical treatment and most sanctuaries of this kind had excellent sources of good water [36].

In dry Greece, the emerging city-states in the Archaic Age took great effort to secure good water supply. Ostensibly, the Athenian magistrate Solon (ca 630–560 BC), through his extensive reforms, aimed at providing water for the Athenians, including provisions listing technical details for the depth of well-digging and the distance between the wells. Moreover, to prevent infections, measures were taken to guard the water supply from contamination. Later on, the Laws of Plato (ca 424–384 BC) advocated sound principles for management of city water supply as well as stipulating ethic principles for the surroundings of spring-fed fountains. This included the planting of trees, construction of fountain houses, and observance of how the water supply would often be associated with sanctuaries and sacred groves [13].

Moreover, in the Classical period, the Greeks made an effort to improve strategies and technologies for water treatment. One prominent example of this is the Northern Greek city-state of Olynthus, west of the Strymon River, which developed water filters very similar to the those contemplated more than 1000 earlier by the Minoans. In both of these examples, the water supply system included coarse underground sand filters intended to clean rainwater before entering underground cisterns (Figure 6). As recently demonstrated, however, cisterns were not designed to facilitate constant inflow and outflow, a fact which called for a solution, such as the course sand filter [37].

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

Figure 6. Olynthus bottle-shaped cistern with a small tank for pretreatment, including the capture of debris and sediment: (**a**) plan and (**b**) cross-section ([37]).

2.2.3. Roman Period (31 BC–476 AD)

The Romans improved existing hydro-technologies at a larger scale and initiated their diffusion throughout the Empire [38,39]. These are first discussed extensively in the treatises of Marcus Vitruvius Pollio, a Roman architect and engineer who lived in the ca.

1st century BC ([32]. New techniques and materials were applied to set up thousands of highly advanced water systems for cities, mines, villas, and for irrigation ([40,41]. As an example, a model of two-story, four-chambered settling tanks (piscina limaria) in the Virgo Roman aqueduct on Pincian Hill in Rome is shown in Figure 7.

Figure 7. Model of the settling tanks (piscina limaria) on the aqueduct Virgo in Rome (Roman Civilization Museum in Rome, by permission of L. W. Mays).

Roman law determined the ways to remove water and impurities from private and public areas and buildings and channel them out of the cities to protect public hygiene. The rights and obligations of the citizens were defined in Roman legislation [16]. More specifically, citizens had the right to a drain or a sewer from their house or land through the neighbor's land or house [42].

Hygiene in ancient Rome was promoted via the famous public baths and toilets in which water was supplied via long-distance aqueducts, all with generally high standards of cleanliness for the times, and subject to regular maintenance work [43]. Public toilets were commonplace and provided by running water from aqueducts (Figure 8), or from waste water of baths [44]. For example, Ephesus was founded in the 10th century BC as an Attic-Ionian colony. It is also one of the largest Roman excavation sites in the eastern Mediterranean. In the center of Ephesus, there was an uncovered pool that collected rainwater and provided refreshment on hot summer days. The public latrines were built as part of a larger construction project—the so-called Scholastica Baths, which provided grey water for flushing toilets. In winter, the latrines were kept warm by an underground heating system that discharged steam from the baths.

This, despite some awkward habits such as the use of a communal toilet spongia or tersorium (a natural sea sponge, fixed on a stick, which was rinsed in a bowl of water and vinegar after use) as a means of intimate cleaning, since toilet paper was not an option at the time [45]. At its peak (early 2nd century AD), Rome is believed to have had about one million inhabitants and it was the most populated city. According to historians, there were at least 144 public latrines in Rome during late antiquity, and although most of them were located next to public baths, only a small number were connected to the main sewage system. Public urinals consisted of buckets, called *dolia curta*, which were regularly emptied by dedicated workers (*stercorarii*) that sold their content to fullers for cleaning wool and other uses. The admission fees in public baths were low to make them accessible to most people: one-quarter of a denarius "dime" (1/10th) for men, one for women, and free for children; however, hygiene in the Roman World was limited to those who could afford those fees, since running water from the aqueducts did not supply all the buildings [46].

Figure 8. Roman toilets in Dougga, Tunisia. Photo C. Passchier.

However, despite the empire's sanitation technology, recent studies of ancient feces from more than 50 archaeological sites cast doubts on how effective the Roman sanitation system was at improving public health. Intestinal parasites prevalence, like whipworm (*Trichuris trichiura*), roundworm (*Ascaris lumbricoides*), and *Entamoeba histolytica* (causing dysentery) were widespread [47]. The study identified bathhouses as a potential hotspot for disease transmission since, although Romans designed them to promote and improve public health, many were poorly maintained and had poor-quality water. The warm, moist environment would provide an ideal breeding ground for parasites. The prevalence of intestinal and ectoparasites may suggest that Roman toilets, baths, and sanitation rules had a lesser impact on public health than commonly thought; however, they might have avoided many worse situations [47].

Only the upper class enjoyed running water from lead pipes connected to the aqueducts; however, in Pompeii almost all the houses, save for the poorest, had water pipe connections fitted with taps, and wastewater drainage into sewers or trenches. Terra-cotta pipes were used in the sewage drains that ran from the few homes that had it. In multi-story residential buildings, there were no toilets and people had to make do, relieving themselves in pots that were emptied into larger vats which were in turn emptied into cesspools located throughout the city from where the so-called *stercorarii* would collect the waste at night, selling it to farmers as fertilizer. Often, however, excreta were poured directly onto the streets [48].

Bathhouses were present in any population center in Roman times, up to private bath houses in Roman villas [49,50]. The baths were mainly a means for relaxation, although the skin was cleaned using olive oil, anointing, and then scraping off the oil with any remaining dirt [51]. A swimming pool in a Roman bathhouse is shown in Figure 9. Soap was known in roman times as "sapo" (Pliny H.N. 28.191) but, probably, it was not widely used [52].

The first sewer in Rome, created as an open channel to drain stagnant water from the marshy area of what later became the Roman Forum, was built approximately between ca 800 and 735 BC. As Rome grew, so too did the canal, with changes of direction corresponding to new civic buildings, and the addition of side channels. In the second century BC, it was covered to become Rome's first underground sewer system. The largest conduit (*Cloaca Maxima*) was 4.2 m high and 3.2 m wide and stretched for several km [53]. Views of part of the *Cloaca Maxima* are shown in Figure 10. After supplying public baths, fountains, and palaces, aqueducts were channeled into the sewer system, where the constant supply of running water kept them clean and unobstructed. When constriction occurred, convicts were sent to remove them, according to Pliny the Younger (Epistles, X.32.2). Since the original purpose of the system was to drain marshy water (human waste was mostly thrown onto the streets or carried away for farming), it principally served the public areas of the city, providing little to no hygienic relief for crowded residential areas. Romans employed special officials (aediles) to supervise the sanitary systems: they were responsible for the efficiency of the drainage and sewage systems, for cleansing and paving the streets, preventing foul smells, as well as for the general oversight of taverns, baths, and other water supplies [54].

Figure 9. Swimming pool in a Roman bathhouse, Bath, UK (Photo Cees Passchier).

Roman aqueducts provided cities with water of varying quality, primarily depending on the quality of chosen water source, changing environmental (earthquakes, floods) or anthropogenic factors (human interference through contamination, using fertilizer for agricultural activity, etc.), and the frequency of the maintenance work to preserve the high-quality standards of this water supply [39]. City aqueducts were built over a period of about 800 years, from 312 BC until the end of the Empire, and peaked around the 1st century AD. They were amazing feats of engineering for that time. More than 2000 Roman city aqueducts are attested in literature and many more must have existed [40]. Rome alone had around 11 aqueducts supplying freshwater from sources as far as 92 km away [55]. The longest city aqueducts, such as that of Cologne, 95 km [38], Carthage, 132 km [56,57], Apamea, 150 km [58] and Constantinople, 426 km [59], provided their cities with up to one m^3 of fresh water per second [55].

Evidence concerning these aqueducts remains throughout the former Roman Empire, some still performing their function. Although the most recognizable features of Roman aqueducts are the stone arched bridges, still seen today, these made up only a small portion (only about 20%) of the more than 5000 km of aqueducts built throughout the empire, as tunnels, canals, and pipes made up most of their structure [39,40,53].

The Aqua Virgo, constructed by Agrippa in 19 BC under Augustus' reign, still supplies water to Rome's Trevi fountain and it is shown in Figure 11 [11]. Though earlier

Egyptian, Minoan, Greek, and Indian civilizations had also built aqueducts, the Romans improved their structure and scale, and built extensive networks across the territories they controlled [38,39].

Figure 10. Views of the *Cloaca Maxima*, part of the subterranean sewer system in Rome, Italy [54].

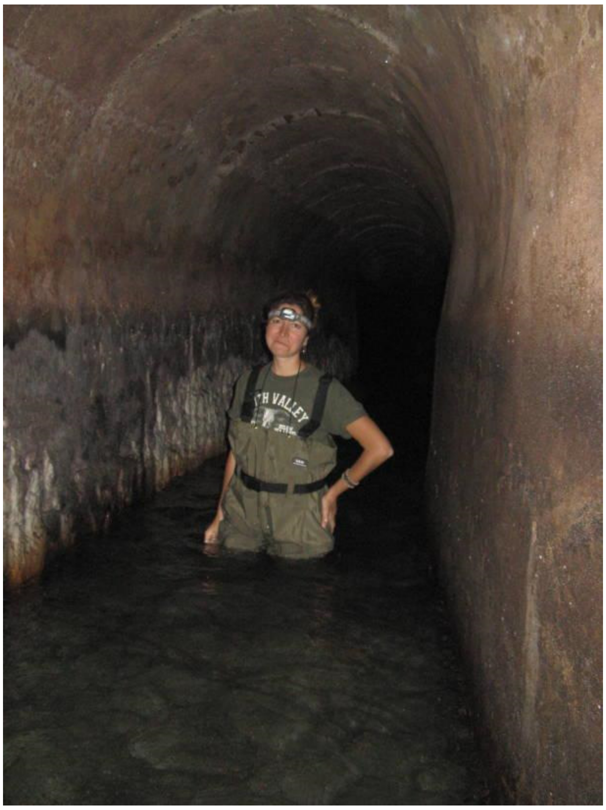

Figure 11. The AQUA VIRGO in Rome is a Roman aqueduct that still transports approximately 1 m^3/s (Photo Cees Passchier) [11].

Roman city aqueducts differ considerably from modern water supplies in that they provided a constant flow of water for drinking and bathhouses [38,39]. Although taps were known [60], they were not normally used to close water pipes at their ends, to avoid spillage of water: the principle was that water was flowing continuously and, either used or not, it would end in the sewers of cities, thus providing a constant means to flush the sewers [38].

Most aqueducts were fed by springs or groundwater while only a few city aqueducts, such has Segovia, Cahors, Syracuse, and Corycus, were fed by rivers, and these were mostly in non-inhabited areas [40]. It is not known whether this preference for springs was linked to the concept of hygiene, or whether it is simply because springs are a more certain and constant source of water. This choice certainly improved the general hygiene of cities.

The remaining ruined Roman water structures of modern days cannot say much about ancient Roman water management. To understand the strategy of Roman water management, and the way an aqueduct worked for centuries, we need to look for other archives, directly in relation to these water systems [61–63]. Fortunately, in most cases, the Romans tapped karstic sources, which left behind hardened calcium carbonate deposits wherever it flowed on surfaces of terra-cotta or lead pipes, masonry channels and in any other water structure [39]. The origin of the water, water chemistry, environmental changes which affected water quality throughout the active years of an aqueduct, and finally water management in terms of cleaning can all be read from the hardened carbonate deposits [64]. Aqueducts had to be constantly repaired and cleaned of carbonate, plant roots, and objects that fell into the channels, and a strip of land above them kept them free of trees and damaging activities [38,39]. Evidence for repairs, cleaning, or other means of modifications/adaptations can be found in carbonate deposits. Roman water management should be categorized and studied as a special subject, besides the engineering of water structures. Indeed, the annually laminated calcium carbonate archives tell us more about the quality of water management [64].

An exceptional example of the Roman water management strategy is the aqueduct of Divona (Cahors, France) which stores at least 88 years of history of Roman water management [63,65]. Sustaining water quantity, quality, and availability depends on structured work with a certain periodicity. This is attested in the calcium carbonate archives of regular cleaning traces at Divona (Figure 12). The cleaning traces with certain periodicity prove that a continuous water supply was a priority and a certainty in Divona, similar to the Byzantine Valens aqueduct (Section 2.2.6): stable oxygen and carbon isotope profiles were constant throughout 16 regular cleaning events, and this can only be explained with cleaning/maintenance breaks of less than one month [41]. More information are in the http://www.mdpi.com/authors/references, accessed on 15 April 2023.

As the estimated use of the aqueduct of Cahors spans up to 300 years, the recorded 88 years of deposition shows us a changing cleaning strategy too: most likely the deposits studied here are from late antiquity, and there must have been a complete cleaning of 200 years of deposits in an efficient way, similar to the Valens aqueduct (Section 2.2.6). This attests to the changing socio-economic circumstances throughout the Empire, besides the deterioration in the maintenance structure and declining water management quality in and during the 3rd century AD, notoriously known as the empire-wide downturn phase of the Roman prosperity and stability.

2.2.4. Han China Dynasties (ca 206 BC–220 AD)

Since ancient times, China has been one of the most populous countries in the world. The expansion of the scale of human settlements led to the increase of ancient Chinese people's demand for clean water. About 4000 years ago, in the legendary Dayu era, Chinese people invented the technology of well sinking to obtain clean and sanitary water. Cities with large populations used rivers or lakes for water diversion and drainage. During the Warring States period (475–221 BC), there were some relatively systematic underground water supply pipelines in Dengfeng City, today's Henan Province, which is slightly similar to contemporary water supply facilities [66]. The well had a cover, a fence, and a public water drawing tool. In early spring, people used to dig wells to ensure the cleanliness of well water.

Figure 12. Cleaning traces in the aqueduct of Divona, with marks made by a scraping tool (Photo Cees Passchier).

With the development of cities in the Han Dynasties (ca 206 BC–220 AD), water conservancy connected the natural water environment with the human environment. People made full use of natural conditions near mountains and rivers and built their residences in places with suitable climates, sufficient sunshine, and convenient water sources. Additionally, they used simple water conservancy measures to provide engineering facilities for water storage and drainage to create a clean water environment.

Chang'an, the capital of the Western Han Dynasty, provides us with an illustrated example in this respect. This city is located in today's Xi'an City, Shaanxi Province. The terrain is high in the south and low in the north. Many rivers flow into the Wei River from south to north. Given the expansion of the palace and capital during the reign of Emperor Wu of the Han Dynasty, the old water source was not enough to facilitate the construction of the water supply project Kunming Lake in the fourth year of Yuanshou (119 BC). The artificial lake covers an area of 10 square kilometers. People built many water channels to bring the lake water into Chang'an City to the east and then into the Weihe River to the northwest. As the famous work of the Warring States Period (475–221 BC), "The Spring and Autumn Annals of the Lu Family", said: "The running water does not rot, and the hinge of the household does not rot". The lake provided clean domestic water for hundreds of thousands of citizens in Chang'an and was also conducive to sewage discharge.

2.2.5. The Gupta Period (ca 319–467 AD)

Following the Indus Civilization, toilet facilities emerged in the Gupta era (ca 4th to 7th Century). The Kolhua archaeological site contains Kutagarshala Vihar. Kolhua is a village in the Saraiya Block of Bihar State's Muzaffarpur District. The Kutagarshala is a representation of the location where Buddha used to reside while visiting Vaishali during the wet months. Three stages of its construction have been made visible by excavations [24].

It was initially a little Chaitya constructed in the Shunga-Kushana era. It was then expanded in the second phase during the Gupta era. Finally, it was transformed into a monastery in the third phase by adding several partition walls. A bathroom is attached to the southern wall of this monastery. It was built during the Gupta era, most likely for the Nuns, and it was designed for latrine use. It is divided into three pieces, each measuring 88 cm in diameter and 7 cm in thickness. Each piece has two holes, one large (18 cm in diameter) for the face and one smaller (03 cm in diameter) for the urine [24]. The rim peripheral of the pan was a little higher than our current toilet pans. The toilet system in the ancient world was used for a unique collection [24].

2.2.6. Byzantine Period (ca 330–1453 AD)

At the beginning of the Byzantine period, the Roman water technology tradition was still prevailing. More than using pre-existing Roman water systems, new systems were built. For instance, the Aqueduct of Valens was built in the late 4th century AD, to supply Constantinople [67–69]. Portions of this aqueduct can still be observed inside the city walls (Figure 13). Many other sections can also be observed outside the city, notably incorporated in the 16th-century AD aqueduct of Sinan [67,68].

Figure 13. The Roman aqueduct of Valens was used for the water supply of Constantinople (https://en.wikipedia.org/wiki/Aqueduct_of_Valens) (assessed on 15 April 2023).

The aqueduct of Valens was the longest in antiquity. It highlights the significance of organizational skills when it comes to providing continuous water to one of the most populated cities of ancient history [59]. This aqueduct had two channels, from the 4th and 5th centuries, with a combined length of 426 km and a long section where both run alongside. The Byzantine water supply and management never ceased except during the barbarian invasions, and it provided continuous water to the city of Constantinople for about 700 years. The continuity of this water supply was only possible with intelligent water management, where two-story double channels were operating in tandem to substitute each other during the periods of carbonate removal [59]. Hence, even though the 4th-century upper channel was closed for repair works and cleaning of carbonate, the 5th-century lower channel was supplying the city with continuous water (Figure 14). This well-planned cleaning strategy must have been applied for at least 650 years, as laminated calcium carbonate deposits with an annual resolution of the Valens aqueduct only represent 22 years of water management and environmental history of 12th century AD. As the last layers of carbonate stratigraphy do not show any abnormality in the recorded temperature profile, the aqueduct was probably abandoned after a strong earthquake, which destroyed the longest water supply line in history, and caused a decline in the city population and a return to the original Hadrianic aqueduct system from the 2nd century. The water management of the Valens aqueduct seems to be the best example of exceptionally efficient maintenance by Byzantine workers.

Figure 14. The 5th century channel of the Byzantine aqueduct of Constantinople (Photo Cees Passchier).

Another example of a remarkable water system of the Byzantine period is found in Apamea (in Syria). At the end of the 5th century AD, the water supply system inside the city was completely reworked. Excavations conducted at the beginning of the 2000s have shown that a large aqueduct inside the city limits and numerous pipelines were built and used for more than one century (Figure 15). This shows that the inhabitants of the city were able to build a new water supply system, which has been proven, through computational fluid dynamics simulations, to be of high quality [70]. Care was given to the supply of quality water as, for instance, some sedimentation tanks were placed along the pipelines (Figure 16). There are no remains of the internal aqueduct in the southern part of the city. However, archaeological excavations have shown that, around the mid-6th century AD [71], three large buildings were equipped with hydraulic systems, two *nymphaea* and a private bath. In addition, hydraulic calculations have shown that these systems were necessarily connected to a working aqueduct, to permanently supply them with water (Figure 17). This highlights the important link between water and wealth in the Byzantine period of the city [71].

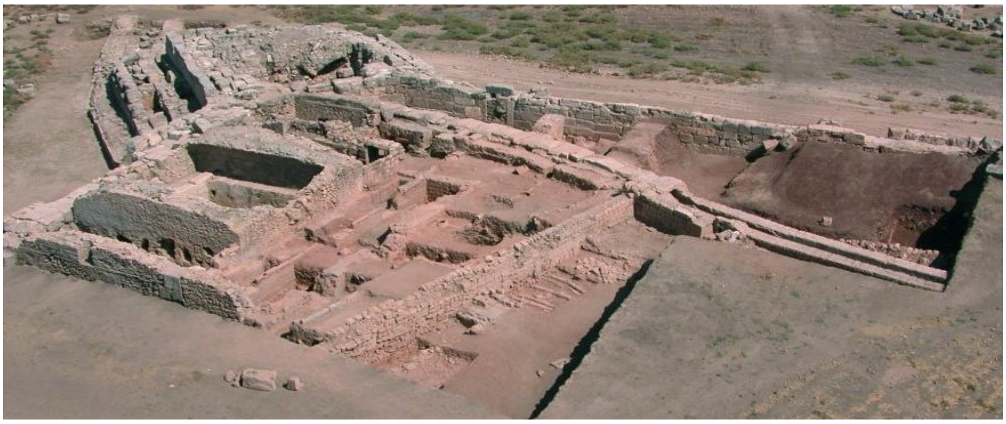

Figure 15. Excavations in the northeast area of the city of Apamea. They revealed a water system constructed at the end of the 5th century AD ©CBRAP (Centre Belge de Recherches Archéologiques à Apamée de Syrie), permission has been given.

Figure 16. Terra-cotta sedimentation tank, operated during the Byzantine period, was excavated in Apamea. The picture was taken by one of the authors [70].

Figure 17. *Triclinos* building in the Byzantine Apamea. North apse-shaped basin in the main cold room. The picture was taken by one of the authors [71].

As already mentioned, baths were highly popular during Byzantine times. Archaeology has shown that, in numerous cities of the Byzantine Empire, baths constructed during the Roman period were extensively reworked and expanded. For instance, in Bosra (south of Turkey), the baths at the south of the city were developed during different phases and they reached their maximum size in the 4th and 5th centuries AD [72]. The large dome of the east-located cold room is still very well preserved (Figure 18). In Perge (in Turkey), the monumental bath complex [73,74] was (re)constructed through several phases between the first century AD and the 5th century [75,76]. For instance, the hypocaust of the hot baths is very well preserved (Figure 19).

Figure 18. East caldarium in the south baths in Bosra. The picture was taken by one of the authors [72].

Figure 19. Hypocaust of the hot baths in Perge. The picture was taken by one of the authors [72].

However, some authors point out a decline in water system quality later in the Byzantine period [77]. At certain places and from a certain time, the aqueducts were no longer operated, and the inhabitants constructed cisterns to collect rainwater [78]. For instance, in Smyrna (the actual Izmir, Turkey), large cisterns (Figure 20) were constructed at the end of the Roman period under the agora [79,80]. The largest one has a ground floor area of more than 150 m^2. In Bosra, there is a large cistern in the southeast area of the city (Figure 21) that was built by the Nabataeans and used for centuries, notably to provide water on the road to Mecca [81].

Figure 20. Cisterns under the western stoa of the agora of Smyrna. Picture taken by one of the authors.

Figure 21. Large cistern in the northeast area of Bosra.

As far as toilets are concerned, several examples of multiple-position toilets could be found in the monasteries [15] but single toilets were the common situation in Byzantine houses [16]. Concerning drainage and sewerage, it is documented by written sources that in the Byzantine Empire cities central and secondary sewers and drains, the neighborhood ducts network and domestic drainage for rainwater were used [16]. A distinction between public and private sewers existed and inhabitants had the right to connect their sewerage to the central public ducts (Digesta 43.23.1, 3). Maintenance and cleaning of the public drainage network were carried out by a special group of employees [16]. Based on the scripts, sewerage and drainage networks existed only in towns where disposal of wastewater was possible (sea, lake, or river close to the town) [82].

2.2.7. Medieval Times (ca 476–1400 AD)

In the western Mediterranean, the lack of knowledge and skillful people to build long-distance aqueducts like the Romans did was also noticeable in Visigothic Spain. Many important cities were still using and maintaining their Roman aqueducts until the beginning of the 6th century. Bishops ensured the maintenance of aqueducts to enhance their political position. The aqueduct of Seville was in use until about the 6th century. In Reccopolis, which was founded by King Liuvigild during the 6th century AD, a new aqueduct was built, almost as big as a Roman aqueduct [83].

One of the aqueducts in Merida was renovated for use, but due apparently to a lack of skillful workers, the roof structure was not completed and this attempt failed [84].

Water technology continued to flower in the Islamic world, notably in El Andalus in Spain. A famous example is the reused Roman aqueduct of Cordoba, which supplied the Caliphal city of Medinat Az-Zahara (مدينة الزهراء) in the 10th century [85].

In Rome, the Ostrogothic period was also remarkable, following Roman engineering examples and ideas, and this was made possible by extensive maintenance and modification works [86].

The Salona aqueduct in Croatia was also active until about the 7th century. The aqueduct was supplied by the big karstic source of Jadro (2.7 km distance). Although the distance was not great and therefore it was a short aqueduct, the carbonate deposition was 0.5 m thick. The aqueduct supplied water to mill activity and it was destroyed by an earthquake. The source of Jadro supplied water to Split two centuries after this event and is still active today.

Little progress was made in water treatment, sanitation, and their connection to the public health field in the high Middle Ages. During that period, also known as the Dark Ages, technological development, especially that related to water quality, was minimal due to the lack of scientific innovations and experiences [87]. The diffusion of ideas and knowledge was interrupted for some time as defense and security became more important than transfer of knowledge. Therefore, people in the Dark Ages returned either to existent wells and cisterns, built new ones, and improvised other ways to find water. Water supply extracted from rivers or wells provoked the problem of pollution due to the discharge of wastewater and other factors. To face that problem, people started to bring water from unpolluted rivers located outside the cities. Examples of some innovations and applications are certainly present for castles and especially monasteries [88].

2.2.8. The Mughal Empire (1526–1761 AD)

Before more than 300 years of Muslim rule in India, there was little social awareness about the importance of public cleanliness. Social understanding of the benefits of public sanitation was non-existent. The phrase "sweeping and scavenging" seems to have evolved into a legitimate profession with the arrival of Muslims in India. The Mughal Kings founded the Gushalkhana (bathroom) institution in India in 1556. India's heat and dust obliged the Kings to build opulent bathing and massage facilities [23].

Muslims created and built a system of latrines for their ladies in purdah. Prisoners had to scrub latrines, bucket privies, and dump nightsoil at far-off locations. When they were let free, society did not accept them, so they created a separate caste and kept scavenging [89].

The royal palace of the Mughals had bathrooms designed just for the monarchs, royals, and the aristocratic class. These bathrooms had a lidded connection to substantial septic tanks. The Shudra (Untouchables) was used to clean and empty the tank once it was full. Small toilets were carried by the King's servants when he was away from his palace. After defecating, they used to wash it immediately [89].

Arab traders and Mughal rulers constructed bathrooms on their property so that women would not be exposed while defecating. The filthy work had to be done by someone else because these latrines were dry. To clean up the filth left by the kings and their queens, a class of manual scavengers emerged in India [90].

In 1556 AD, the Mughal King Jehangir constructed a public latrine in Alwar, 120 km from Delhi, for use by 100 families [23]. The 16th-century fort, which was built on a hilltop on the outskirts of Jaipur, Rajasthan, was modeled after the Mughal Forts of Fatehpur Sikri and Agra in 1569 AD and had good bathroom facilities. Again, embedded from the Mughal emperors, the king and his harem had exclusive use of the Diwan-e-khas portion of the Amber Fort, with appropriate seclusion for them. As a result, the Diwan-e-khas had three rooms, each of which included eight apertures for feces. This figure demonstrates that, even with a dozen users, there was no need for a queue. Each hole in the earth was filled with human excrement in proportionately sized compartments. Its operation was similar to the feces holes near Haremsara at the Fathehpur Sikri Fort. The Halalkhors (scavengers) had an opening in the back of each of the aforementioned rooms through which they could manually collect excrement for disposal in safer locations [89].

3. WASH in Early and Mid-Modern Times (ca 1400–1850 AD)

In general, the Ottoman period is more or less a continuation of the Medieval Times. At that time, very little progress was done in water and wastewater treatment and sanitation.

Hygiene and cleanliness were important in Iran even before Islam. After Islam, particularly during the Safavid period, in Isfahan, there were approximately 300 public bathhouses. This well shows the importance of sanitation and also the level of urban management and development in Iran (Persia) [91].

There were various types of public bathhouses in an Iranian city:

Bazaar Bathhouses: These kinds of bathhouses were located in the downtown for citizens. Bazaar Bathhouses were part of a larger complex consisting of a mosque, a religious school, and a bazaar. The working hours of these Bazaar Bathhouses were divided into two different shifts, one for men from 4:00 a.m. to 9 a.m. and the other one for women from 10 a.m. until the afternoon. In addition, in some cities, there were separated Bazaar Bathhouses for men and women, which were available full time.

City Gate Bathhouses: *City Gate Bathhouses* were located in cities that were visited by foreigners, including tourists, merchants, and sometimes students. *City Gate Bathhouses* were often found close to the city gates to provide a cleaning spot for the visitors before they accessed the city.

Caravanserai Bathhouses: They were roadside establishments built to accommodate visitors on their long trips. Along with other convenience facilities, *Caravanserai Bathhouses* often had bathhouses to help visitors for washing and cleaning. The water used in these types of bathhouses was supplied by Qanat systems.

Hot Spring Bathhouses: The surroundings of natural hot springs were used as a place for bathing due to their health benefits, particularly in the Qajar era [91]. Some Persian Baths (Hammam) are shown in Figure 22.

Figure 22. Persian Baths (Hammam) (adapted from [7,91]).

During the same period in China, the Ming Dynasty (ca 1368–1644 AD) developed a very strict urban water management system. In the first year of Chenghua in the Ming Dynasty (1465 AD), the stone tablet of "The Record of the Newly Opened Jiqu" was inscribed with the "Water Regulation" of that time. It was stipulated that the management personnel had to perform their respective duties, inspect and repair the water conservancy facilities. Water had to be supplied to irrigation and domestic water on time based on the available quantity. Each wellhead was maintained by a local household, and it was forbidden to throw garbage and debris into rivers and wells.

In addition, it was not allowed to open hotels near the canal, to accumulate grain and pollute the canal water in the city. Furthermore, it was necessary to prevent insects and rats from penetrating holes. These regulations played an important role in saving water in cities and ensuring the health of residents [92]. Some medical books of the Ming Dynasty also noted the importance of the safety of drinking water, requiring that it must be precipitated, clarified, and boiled before drinking.

In ancient Chinese cities, systematic drainage facilities were built to drain surface rainwater and domestic sewage. The total length of drainage ditches in the whole city of Beijing, the capital of the Qing Dynasty (ca 1644–1912 AD), was 400 km, and there were specially-assigned persons to manage and repair them regularly. At the end of the Qing Dynasty, due to government corruption, officials embezzled the funds assigned to maintenance, and therefore repairs of ditches were perfunctory; as a result, a large amount of water overflowed on the surface during heavy rain, provoking the collapse of houses, blocking of roads, and leaving people without shelter. In addition, to prevent flooding, the city gate could not be opened, and the grain and vegetables outside the city could not be transported into the city; this resulted in rising prices and complicating people's livelihood. Thus, it is shown that high environmental protection awareness, moral conduct, and a sound legal system are the basic conditions for ensuring sufficient water environment protection.

4. WASH in Contemporary Times (1850 AD–Present)

The modern age of sanitation started in Europe between the 16th and 19th centuries when pail closets, outhouses, and cesspits started to be used to collect human excreta. The "invention" of the flush toilet in 1596 (adopted on a large scale only three centuries later) by Sir John Harington, godson of Queen Elizabeth, was a step forward from common toilets used by Romans (also with continuous water flow for feces removal). However, the first patented water closet (WC) appeared in 1775 by Alexander Cummings, a watchmaker in Bond Street (British Patent Reports, Vol. XIV, No. 1105) and wealthy Londoners gradually adopted it. However, as late as 1847, one-third of properties in the wealthiest areas of London still lacked this modern convenience [22]. The first toilets were connected to the existing sanitary infrastructure, i.e., cesspools, not sewers, and many of the various London sewer authorities forbade households from connecting water closets to their main drainage due to concerns about flooding and street drainage. The greater volume of fouled water entering the cesspool once WCs were installed, however, meant that pits filled up quickly, and could not drain away quickly enough; so, the surrounding ground turned into damp and foul-smelling mud. Waste had to be pumped out more frequently. Therefore, between 1800 and 1830, homes were gradually connected to the main street drainage. However, in 1827, the first public health scandal related to sewage occurred: journalist John Wright exposed a local private waterworks company, which advertised its supply of water as 'always pure' and 'constantly fresh', for drawing water from the Thames just within yards of the outfall of a major sewer and distributing it to thousands of wealthy customers without any treatment (at the time, mostly settling and filtration). Therefore, the London elite was receiving diluted excrement for drinking, cooking, and laundering while paying handsomely for the privilege! On the other hand, there was no contemporary scientific proof that foul water was linked to any particular illness since the medicine of that time believed illness to be caused by an "imbalance in the body's natural equilibrium" [93].

The development of plumbing, latrines, and personal toilets by several inventors enabled the organized collection of human feces and their distribution to sewage networks. During the same time, the techniques of water purification, the creation of drinking water and its transport to the human population inaugurated an era where personal hygiene could be easily practiced by everyone. This all culminated with the 19th and 20th century "Sanitation Revolution" age, in which governments started enforcing strict hygiene rules, organized garbage collection, developed public health. Bartram et al. [94] presented a timeline of different actions/targets relevant to drinking water and sanitation (Figure 23). The global water/sanitation landscape has completely changed since monitoring under the United Nation (UN) system began. Compared to 1970s, the global population has almost doubled, while the urban population nearly tripled [95]. The rate of people who are using advanced sources of drinking water (64% to 89% coverage) increased from 2.4 billion (1970) to almost 6.2 billion (2012), while the rate of people who are using basic sanitation (36% to 64% coverage) expanded from 1.3 to 4.4 billion. Nowadays, more than half of the world's population receives piped water at home [96]. Life expectancy at birth has enhanced from 56.5 years to 68.7 years [95], as a result of enhancements in drinking water and sanitation [97,98].

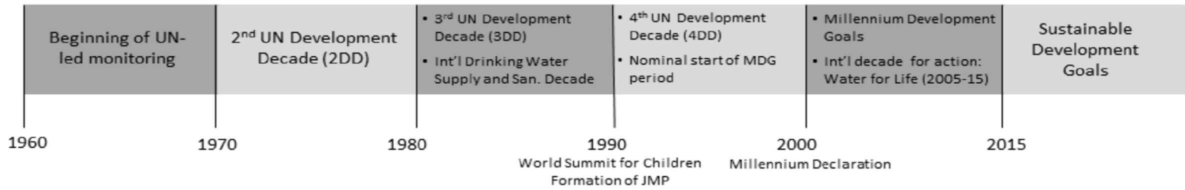

Figure 23. A timeline of different actions/targets relevant to drinking water and sanitation (adapted from [94]).

In the early period of the last century, infectious diseases (e.g., pneumonia, meningitis, tuberculosis, etc.) caused high death rates, which in turn contributed to the reduction of life expectancy. Kramek and Loh [99] reported that in Philadelphia, USA, due to water pollution, typhoid deaths reached several hundred in 1900 [100]. A filtration construction was completed in 1912 and chlorination of the city water supply started in 1913. Consequently, typhoid deaths were dramatically reduced, demonstrating a direct connection between sanitation measures and human health as well as the paramount benefits of technology (Figure 24).

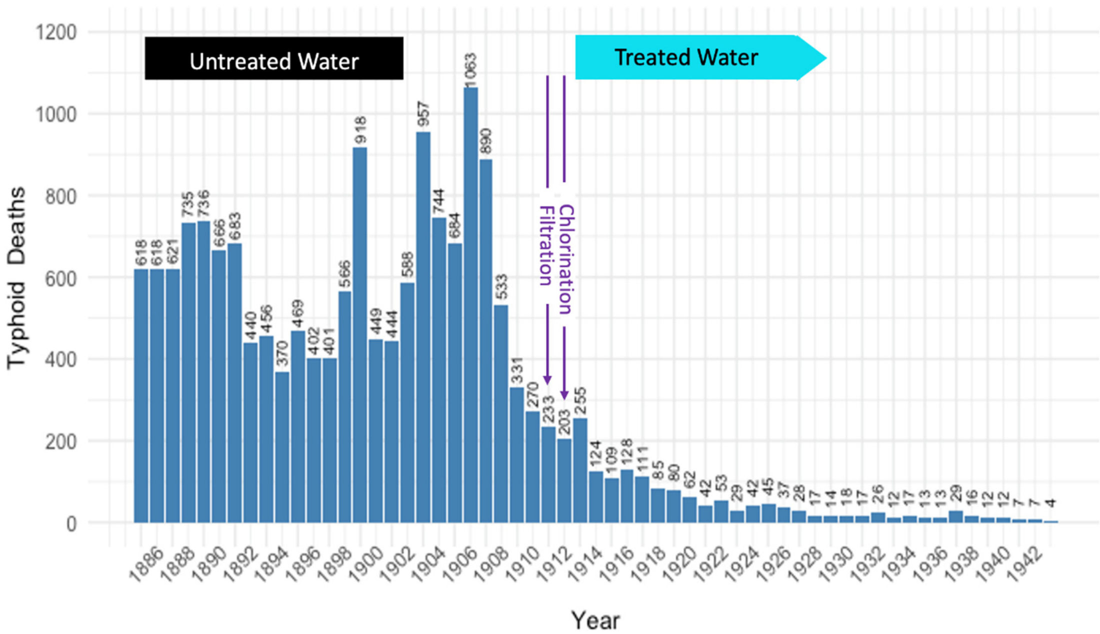

Figure 24. Typhoid deaths in Philadelphia drastically dropped after city-wide water filtration (1912) and chlorination (1913) (Adapted from [100]).

In addition, historical data show a significant increase in life expectancy in the developed world since the beginning of the last century [101]. A historical trend of life expectancy for the entire world is shown in Figure 25 [100].

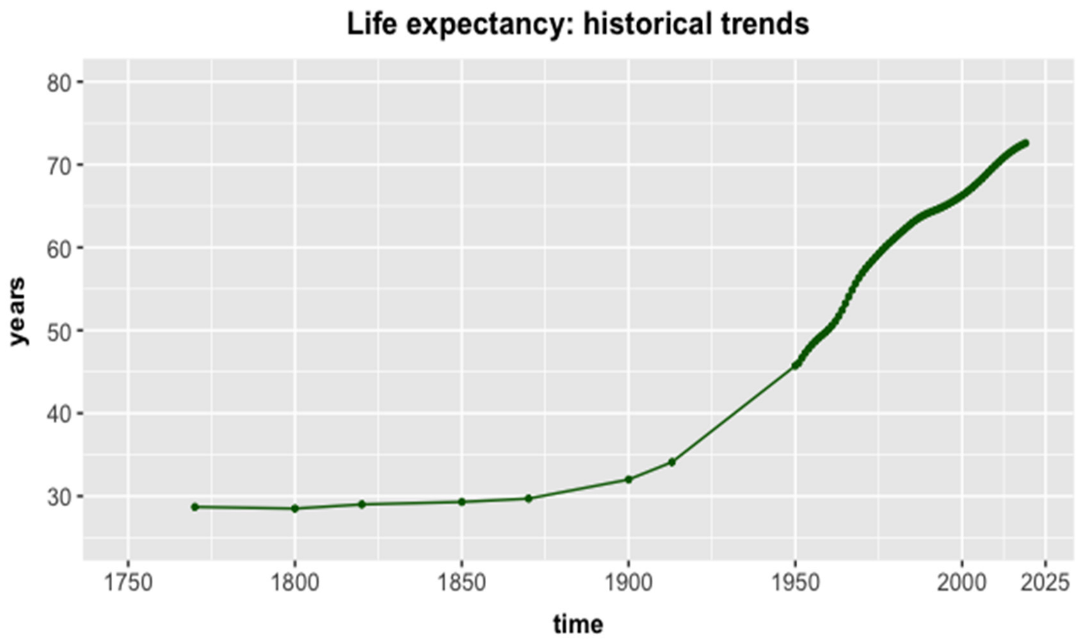

Figure 25. A trend of increasing life expectancy since the beginning of the last century [100].

Disinfection has played a critical role in improving drinking water quality in the USA. In 1908, Jersey City, New Jersey, was the first city in the USA to begin routine disinfection of community drinking water. Over the next decade, thousands of cities and towns followed, contributing to a dramatic decrease in morbidity all over the country (Figure 26).

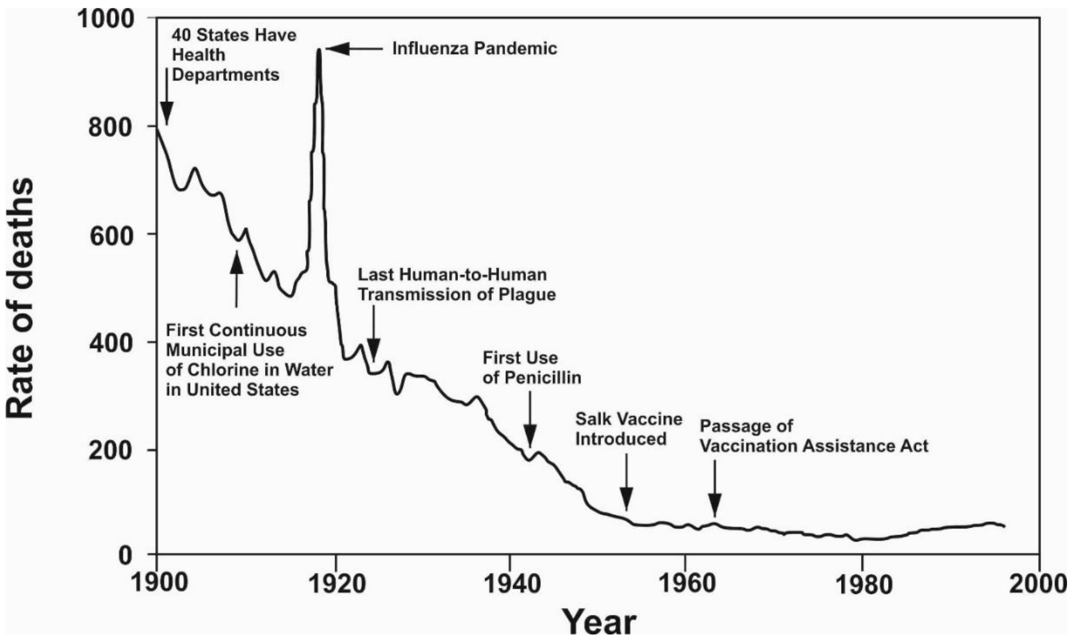

Figure 26. The death rate per 100,000 inhabitants per year from water-related infectious diseases in the USA from 1900 to 1996 (Adapted from [100]).

The life expectancy in Greece was about 44 years in 1920, mainly due to the low quality of potable water. However, in most of the developed world, the quality of potable water highly improved after the 1st World War. In Greece and several other countries, a significant increase in life expectancy occurred after the 2nd World War, which is probably due to the improvement of drinking water quality and hygiene conditions. Thus, the life expectancy in Greece reached 82.8 years in 2022. However, there has been a small decrease (about 0.50 from 2019 to 2021) in the last few years due to the COVID-19 pandemic [13].

Today, safe water, sanitation, and hygiene are crucial for human health and well-being. Yet, millions of people globally lack adequate WASH services and consequently suffer from or are exposed to a multitude of preventable illnesses. Lack of safe WASH negatively impacts the quality of life and undermines fundamental human rights. Poor WASH services also weaken health systems, threaten health security, and place a heavy strain on economies.

India has made considerable strides toward eliminating open defecation nationwide, which has a substantial positive impact on improving access to water, sanitation, and hygiene (WASH). Due to a lack of access to toilets, nearly half of India's 568 million people endured the humiliation of defecating in fields, woods, bodies of water, or other public areas in 2015. Further, 90% of South Asians and half of the 1.2 billion people worldwide who defecated in the open reside in India alone. In addition to eliminating open defecation, UNICEF expanded its goal to include efficient solid and liquid waste management in all towns and cities. The most recent estimates indicate that by 2019, there will be an estimated 450 million fewer individuals without access to toilets. A remarkable accomplishment made only possible by the Government's premier initiative, the Swachh Bharat Mission (SBM) (Clean India Campaign), which is headed by the Prime Minister. The Swachh Bharat Mission, which is currently in phase two of execution, has been proudly supported by UNICEF [102].

In India, efforts to eradicate open defecation have advanced quickly. An estimated 450 million fewer individuals in India are now thought to be publicly defecating. However, we must all consistently practice good hygiene and ensure that we use the lavatories. The poorest residents of rural or urban areas have practiced open defecation more frequently. The absence of routine hand washing and microbial contamination of the water in their homes and communities increase the danger of transmitting diarrheal and water-borne infections. This approach resulted in tones of feces being released into the environment every day, routinely putting India's children in direct contact with excrement. The issue resulted in over 100,000 under-five children dying from diarrhea in India.

Additionally, when employees are sickly and live shorter lives, producing and earning less, and are unable to afford education and secure futures for their children, poor sanitation can impede national growth. The high neonatal mortality rate, which is currently 24 fatalities per 1000 live births in India's health facilities, is a result of inadequate water, sanitation, and hygiene (WASH) services.

The UNICEF Country Program in India places a strong emphasis on collaboration and integration, and WASH is portrayed as cross-cutting assistance that contributes to outcomes in all areas of a child's survival, growth, and development. The WASH program is also poised to reduce infant mortality, prevent malnutrition and avoidable infections, and improve educational outcomes. Swachh Bharat Mission, Jal Jeevan Mission, and WASH in Schools (including "anganwadis") are a few of the government of India's key initiatives that UNICEF supports [103].

The latest data from WHO and UNICEF on access to clean water, adequate sanitation, and hygiene [104] are as follows:

(a) Drinking water: (i) Two two billion people lack access to safely managed drinking water at home. Of those, 1.2 billion people have services. (ii) Between 2015 and 2020, 107 million people gained access to safely managed drinking water at home, and 115 million people gained access to safe toilets at home. In addition, (iii) eight out of 10 people who continue to lack basic drinking water services live in rural areas.

(b) Sanitation: 3.6 billion people, nearly half the world's population, do not have access to safely managed sanitation in their homes. Of those, 1.9 billion people live with basic sanitation services and 494 million people practice open defecation.

(c) Hygiene: (i) 2.3 billion people lack basic hygiene services, including soap and water at home. This includes 670 million people with no hand washing facilities at all. (ii) In

28 countries, at least one in four people have no hand washing facility at home. Additionally, (iii) in rural settings, only one in three people have access to basic hygiene services (such as soap and water at home).

The WASH conditions in the developing world were worst. For example, Haiti in the Western hemisphere, has the lowest rates of access for improving water and sanitation conditions. This situation was probably exacerbated following the earthquake in 2010, which also later in the same year contributed to the rapid spread of the cholera epidemic. Gelting et al. [105] examined the history of WASH conditions in Haiti, considering some factors that have contributed to it. They then considered the situation regarding the earthquake and subsequent cholera epidemic, and the responses to those. Because the current WASH situation has evolved over decades of limited attention and resources in developing countries, it will require sustained effort in the long term in order to improve the situation.

The cost of improving WASH conditions and eliminating cholera in Haiti will be significant. The 10-year plan to accomplish these goals provides an estimate of $2.2 billion U.S. dollars, with more than 70% of that investment going to the WASH sector. However, the potential dividend from these investments is apparent. Experience from Latin America in responding to the cholera outbreak in that region in the 1990s suggests that WASH improvements contributed to the elimination of cholera, as well as reductions in other water-borne diseases [106].

Data from 19 countries of the Region that participated in the United Nations Water (UN-Water) Global Analysis and Assessment of Sanitation and Drinking Water (GLAAS) 2021–2022 indicated that the majority of countries have recognized the human right to safe WASH in their legislation and have further developed national policies, addressing water and sanitation. However, the implementation of these policies and plans is constrained by major financing gaps, in particular for rural sanitation and drinking water [107].

In addition, it is reported by WHO [108] that more than 829,000 people globally die each year from water-related diseases, such as diarrhea as a result of unsafe WASH. Further, according to WHO, seven people die every day from diarrhea in the European Union due to unsafe WASH. The cases of water diseases, including shigellosis, *E. coli* diarrhea, hepatitis A, and cryptosporidiosis, increased in EU countries between 2010 and 2021, as reported in the global infectious disease database. WASH interventions can reduce diarrheal diseases by an average of 30% and significantly limit other water-related diseases [108].

Stunting also represents a powerful risk factor related to 53% of deaths related to infectious diseases in developing countries. Guatemala, Niger, the Democratic Republic of Congo, Mozambique, Bangladesh, and Yemen exhibit an increased rate of stunting among children under 5, which is estimated at over 30% [109]. For example, in Bangladesh, children who constantly drink contaminated water with *E. coli* are at higher risk of stunting than those who are not exposed to such conditions. It is evident that when WASH is coordinated with other health modalities, it can greatly affect reducing stunting. It is reported that nowadays in Niger, most of WASH investments are related to the urban water sector, whereas 90% of the rural population lived without a toilet and 51% without access to clean water supplies.

In addition, it has been reported that in Nigeria, almost one-third of the water source points stopped working in the first two years of use. WASH investments may have the greatest impact on childhood mortality. This is mainly due to the limitation of diarrheal disease. Unfortunately, in Mozambique, budget allocations are not based on transparent criteria and are subjected to political and other decisions at a national level. In the West Bank, local governments have no control over fiscal authority and they depend on their sources of electricity and water [110].

More recently, 19 countries that participated in the GLAAS 2021–2022 survey have integrated WASH regulations into their national plans for COVID-19 prevention, with a specific focus on hand hygiene and healthcare facilities [111]. The importance of WASH is critical for preventing the spread of COVID-19. The World Health Organization's adequate and effective WASH key recommendations to control the pandemic have been difficult to implement in low-income countries and effective coordination between public health and WASH sectors is needed.

Approximately one-third of participating countries had no specific plans for WASH related to COVID-19, and only two countries assessed the cost of WASH-related actions. Several implications related to the COVID-19 pandemic were reported, such as increased demand for water supplies and sanitation systems due to the increased hospital admissions and supply chain disruptions and ingredients shortage due to repetitive lockdowns, leading to a shortage of water disinfectants and other essential supplies [112].

5. Emerging Trends and Possible Future Challenges of WASH Measures Development

Bond et al. [113] presented a timeline for water and sanitation from 3500 BC to 2000 AD (Figure 27). Emerging technologies in terms of WASH can be seen while the world population changes from millions to billions. The world population has increased from six billion at the beginning of the 21st century to over eight billion today (Figure 28).

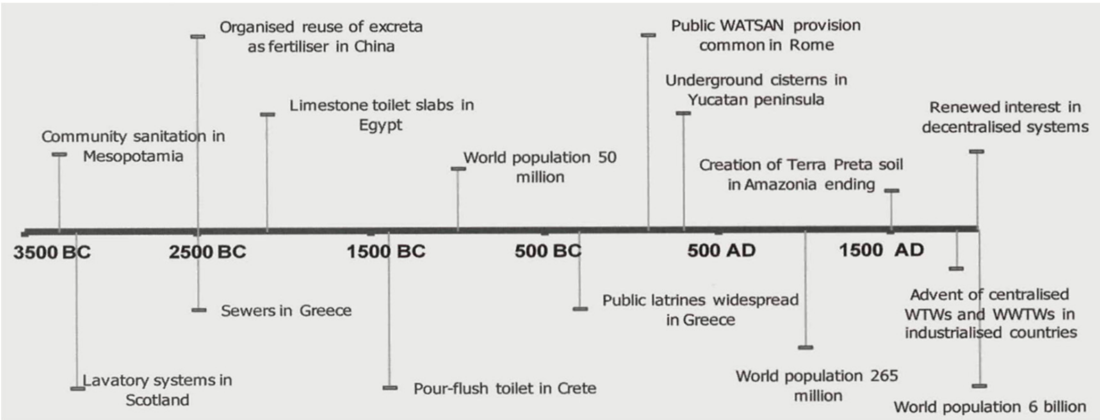

Figure 27. A timeline for water and sanitation from 3500 BC to 2000 AD. WATSAN = water and sanitation, WTWs = water treatment works, WWTWs = wastewater treatment works (adopted from [113]).

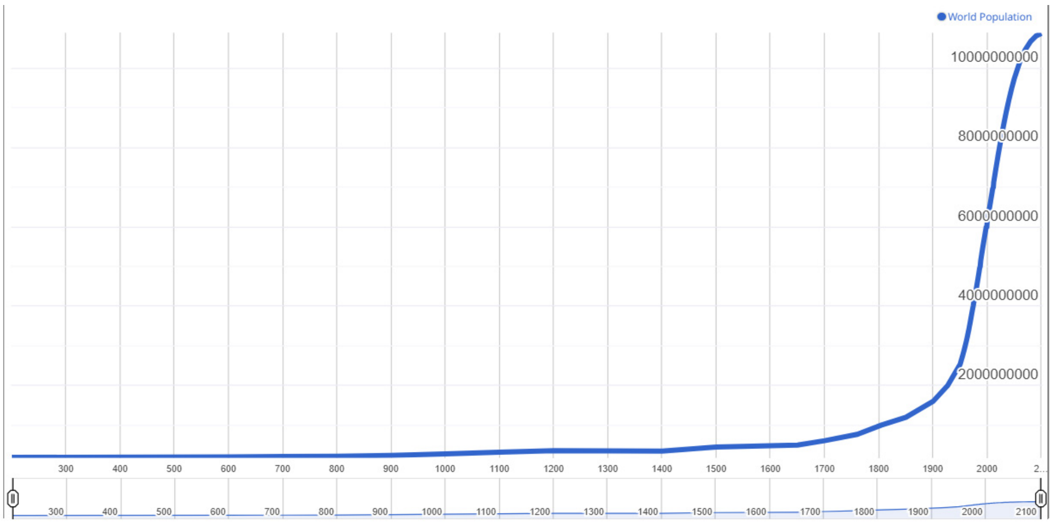

Figure 28. World Population during past, present, and future (https://www.worldometers.info/world-population/, accessed on 15 April 2023).

As the world's population continues to grow, ensuring access to adequate sanitation services will become increasingly important for promoting public health, protecting the environment, and supporting sustainable development. Indeed, the global population is expected to increase in the foreseeable future. It has been projected to reach 9.7 billion by 2050, and 10.9 billion by 2100 [1], caused primarily by the increase in developing countries, particularly in Africa and Asia. Moreover, the population living in urban areas has been constantly increasing over the years. All the above factors put a strain on sanitation systems and jeopardize the environmental quality and human health: increased demand for resources, such as food, water, and housing, can lead to poor hygiene practices and dangerous diseases (e.g., COVID-19), which are caused either by direct contact among humans or indirectly by the production of (waste) water. Poor wastewater management may intensify the pressure on soil and water resources quality, thus impairing ecosystems' services [114–117]. The overall risk for human health is higher in areas with high population density and a lack of inadequate sanitation infrastructure, such as in some developing countries. For example, lack of access to clean water and sanitation facilities can lead to the spread of water-borne diseases, such as cholera and typhoid fever. Poor hygiene practices can also contribute to the spread of other infectious diseases, such as influenza and COVID-19.

Emerging contaminants and pollutants are a group of substances or compounds that have a potential impact on human health and the environment. They include bacterial contaminants, antibiotics, pharmaceuticals (e.g., Endocrine-disrupting chemicals), personal care products, other organic compounds, and industrial chemicals, commonly found in wastewater treatment plants and their effluents [114,118,119]. The spreading of contaminants and antibiotic-resistant genes to the environment, caused by gene transfer during biological treatment processes, can be carried out by a variety of pathways, such as wastewater discharges, irrigation, and agricultural runoff [118,120,121]. The impact of emerging contaminants on human health and the environment is not yet fully understood, but studies suggest that some of these pollutants may be harmful even at low concentrations. Efforts should be made to increase our understanding regarding their fate and the potential risk for ecosystems and humans to develop strategies for mitigating their impact. Climate variability, related to changes in the frequency and intensity of floods, may also be a cause for another reason behind the increased spreading of contaminants and pollutants, which further increases the risk for humans [117].

Cleaning and hygiene can ensure protection against COVID-19. Mainly personal hygiene, cleaning clothes, handling, and preparing food affect COVID-19 [103]. In Europe and in other countries, COVID-19 caused a decline in life expectancy, for the first time in 70 years. While some western European countries, such as France, have returned to their pre-pandemic level, those further east experienced a decline in life expectancy both in 2020 and 2021. Females from 15 countries and males from 10 ended up with lower life expectancy at birth in 2020 than in 2015 [122].

The scarcity of water and poor water quality and sanitation may promote the transmission of SARS-CoV-2 [123]. Adequate access to water, sanitation, and hygiene (WASH) is crucial for protecting human health during outbreaks of infectious diseases [111,124–126]. In low- and middle-income countries (LMICs) with high rates of open defecation, non-effective fecal sludge management, and poor access to safe drinking water, fecal–oral transmission may play a role in virus transmission [127,128]. Hand hygiene is a critical control measure to contain the transmission of SARS-CoV-2 [111,124,129]. WASH measures, such as proper handwashing with soap, could interrupt the transmission of diseases caused by bacteria and viruses [111]. Consequently, hygiene measures, including regular handwashing with soap, regular hand disinfection, and safe disposal of feces, have been promoted as measures for preventing SARS-CoV-2 transmission [129].

The WASH sector in LMICs is attributed with low priority and it is underfunded despite its critical importance to the control of infectious diseases, including COVID-19 [130]. As a result, the majority of the world's population residing in LMICs lack access to adequate WASH facilities [129,131–134]. WASH, malnutrition, and infectious diseases are intrinsically linked [135]. Finally, to protect public health during the outbreaks of infectious diseases including the COVID-19 pandemic, the provision of WASH service is crucial [136].

Food safety is a critical issue in managing the health and well-being of growing populations. As the global population continues to expand, the demand for food rapidly increases. This demand is further affected by changes in diets and lifestyles and urbanization. The quality of food can have a significant impact on human health [137]. Poor food quality can increase the risk of various foodborne illnesses [138]. Food contaminated with harmful bacteria, viruses, or parasites can cause food poisoning and other illnesses, which can even be life-threatening in some cases.

Addressing hygiene concerns is an important aspect of managing the health and well-being of growing populations. It is important to invest in adequate sanitation infrastructure, such as clean water sources, appropriate (waste) water management systems, and clean food production systems. Collaborations, education, and awareness campaigns can also play a significant role in promoting good hygiene practices, such as handwashing and proper food handling, to prevent the spread of diseases. More specifically, effective sanitation requires a comprehensive approach involving a wide range of stakeholders, strategies, and actions. The main goals should be to provide access to clean water; improve sanitation infrastructure; implementation of advanced treatment technologies and management; improve agricultural practices and technologies and food processing and food delivery; improve regulations, strategies, measures, and practices; and increase public awareness about the potential risks [117]. Governments should play a critical role in ensuring sanitation [139], including the development and establishment of a framework for setting sanitation standards, monitoring of compliance, and providing support to communities to meet these standards. For example, the EU, against challenges in the spreading of contaminants and the increased risk to the ecosystems and human life, has introduced relevant legislation and guidelines in specific areas of human activity for EU members [140–144]. However, there is still the need to set specific criteria for the presence of substances in effluents from urban wastewater treatment plants, which should be applied in 2040 [145]. Food safety is another area [137], where the EU adopted a list of measures to protect public health [146]. Moreover, public–private partnerships should have a role in improving sanitation [147–149], involving collaboration between governments, non-governmental organizations (NGO), and private sector entities to implement sanitation initiatives and good hygiene practices (e.g., providing education and resources to individuals and communities).

In developing countries, poor sanitation, particularly in rural areas, caused by the lack of access to basic sanitation facilities, such as toilets and handwashing facilities, highly contributes to the spread of infectious diseases and a range of health issues, including severe water-borne illnesses. This is due to a range of factors, including the lack of infrastructure, limited resources, and poor governance. Besides the human cost, poor sanitation has significant economic consequences, including increased healthcare costs and lost productivity [150]. However, achieving full or partial access to WASH services is still the main challenge for many developing countries [151]. This is of great importance considering that WASH is an important component of the 2030 Agenda for sustainable development, particularly for Sustainable Development Goals (SDGs) 6 [152]. The World Bank has estimated the costs for the global economy by 2030 of adequate access to basic WASH services (USD 28.4 billion per year) and safely managed WASH ($114 billion per year), with the majority of these costs borne by developing countries [150]. Such a cost is equivalent to 0.10 and 0.39 percent of global product for basic and safely managed WASH, respectively [150].

To improve sanitation in developing countries and elsewhere, a multifaceted approach is required, involving governmental actions, public-private partnerships, and social participation [150,153]. This should include prioritization of the actions with an emphasis on investments in WASH, targeting mainly the mobilization of financial resources, given the financial limitations in many developing countries. Financial availability, subsequently, would support the implementation of other critical actions, such as building basic and cost-effective sanitation infrastructure, such as toilets and handwashing facilities, promoting good hygiene practices, improving water quality, and implementing effective technologies and waste management systems. Many countries produce investment plans to meet the target set at a national scale considering the available financing by the government. On this issue, the Organization for Economic Co-Operation and Development (OECD) has developed a tool capable of developing and economically evaluating financing strategies meeting national targets [150]. Additionally, several innovative solutions are being developed to address sanitation challenges in developing countries, such as low-cost toilets that use minimal water and do not require a sewer connection and mobile sanitation facilities that can be used in areas without access to permanent infrastructure. Moreover, decentralized household-centered sanitation should be of concern, particularly in rural areas [117]. Finally, technological tools and new approaches and methodologies are needed to address issues arising from climate variability [149] changing precipitation and temperature patterns, and population growth [152]. The former arises from the increasing frequency of floods that may increase the spread of various pollutants and contaminants.

6. Epilogue

Nowadays, the main idea of implementing water/wastewater historical technologies in developing countries is quite appealing since the features of historical systems would amount to decentralized water and sanitation provision. Before mechanical pumps and computers were invented, simple but efficient ideas and techniques were implemented, which can still be applied today to save energy and to set up cost-friendly and environmentally conscious water systems. This applies to drinking- and wastewater supply systems, irrigation, and electricity-producing micro-watermills. The latest figures indicate that 2.6 billion people do not have access to improved and advanced sanitation. Additionally, 1.1 billion practice open defecation. Hence, there is a vital need for sustainable, regenerative, and cost-efficient water and sanitation technologies, especially in developing countries [113]. Although community/public toilets are not categorized as advanced sanitation systems by the World Health Organization (WHO) and United Nations International Children's Emergency Fund (UNICEF), this can be a debatable premise since examples like Durban in South Africa indicate how public toilets continue to show a water and sanitation way for populated cities. According to the critical need for water and sanitation advanced technologies, particularly dry sanitation technologies, public toilets have important applications in both rural and urban areas [113].

Emergency WASH interventions are vital to prevent the transmission of diseases and also to minimize susceptibility to disease-bearing vectors. NGOs play a vital role in improving WASH policies, contributing to government organizations (GOs), particularly during the post-disaster stage, during both reconstruction and recovery phases. Enhancing contribution between NGOs and GOs has the potential to build a link leading to realistic results. On the other side, a lack of contribution will result in negative outputs, such as infrastructure destruction, loss of life, loss of property, and lack of proper access to an improved WASH system [154,155].

Hygiene is a broad subject with many aspects and a key factor in the prevention of diseases and the promotion of good health. Hygiene has been identified to reduce diarrheal diseases and infections among others, and proper hygiene practices enhance dignity, self-esteem, and prestige in social life. Hygiene can be practiced at the personal, domestic, industrial, institutional, and community level, with several sectors playing various roles in enhancing hygiene as it improves human health. However, it is necessary to incorporate hygiene with sanitation and an adequate and clean water supply, since these go hand in hand [156]. Different countries have made significant efforts to enhance safety, minimize costs, and reduce environmental impact and they continue to invest in infrastructure. It is anticipated further efforts will be undertaken in tunnel engineering, thus contributing to sustainable development in the future.

Achieving full or even partial access to WASH services is still the main challenge for many developing countries, given that WASH is a component of the 2030 Agenda for sustainable development, particularly for Sustainable Development Goals (SDGs) 6. Until then, economic consequences, such as increased healthcare costs and lost productivity, are expected. To move forward, a multifaceted approach is required, including governmental actions, public-private partnerships, and social participation. Emphasis should be given to investments in WASH, targeting mainly the mobilization of financial resources, to support critical actions, such as building basic and cost-effective sanitation infrastructure, establishing collaborations and promoting good hygiene practices, improving water quality, and implementing effective technologies and waste management systems. Moreover, current innovative solutions, such as low-cost toilets that use minimal water and do not require a sewer connection and mobile sanitation facilities, are also important, in the context of the adoption of decentralized household-centered sanitation, particularly in rural areas. Additionally, technological tools and new approaches and methodologies are needed to address new issues arising from climate variability and population growth, expected mainly in low-income countries.

Finally, it should be concluded that: The history of water quality is equivalent to the history of life longevity and quality. In addition, it is indicated that: The study of the past allows us to learn about the present and to make plans for the future. As already mentioned, each year's World Water Day focuses on topics relevant to WASH. Thus, it is devoted to that day.

Author Contributions: Conceptualization, A.N.A. has the original idea and was written the original draft. A.G.C. Reviewing and edited. C.W.P., G.S., A.B. and B.H. contributed to the Roman, Byzantine and Medieval sections. V.A.T. contributed to Section 5 and edited and submitted the manuscript. R.K. Contributed to the Indian parts. Z.M. Contributed mainly to the China part. M.G.R. Contributed to the hygiene parts. Finally, N.D., J.K. and M.V. Contributed to the Abstract, Prolegomena, Iranian parts and reviewed and edited. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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