

Review

A Critical Review of Water Reuse: Lessons from Prehistoric Greece for Present and Future Challenges

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Abstract: Wastewater treatment and reuse has passed through different development stages with time. This study reviews the most essential changes in water reclamation and reuses over millennia, focusing on initial approaches in the Hellenic world and discussing the current situation. Based on archeological evidence and time records, the awareness of the Greeks regarding land disposal, irrigation, and water reuse is highlighted. The latter has evolved into a plethora of applications, with Direct Potable Reuse (DPR) representing one of the last modern frontiers. Currently, advances in wastewater treatment and the spreading of wastewater treatment plants producing large amounts of treated effluents increase the potential for water reuse. This is regarded as a critical option for the continuing protection of water resources and human health, while concurrently satisfying water demand, particularly in areas subject to increased water scarcity. The main constraints in the expansion of water reuse practices are discussed, focusing on wastewater treatment efficiency and quality effluent standards issues, as well as on the lack of motivations related to the acceptability of this practice by final users. Against these challenges, the need for a transition from an “issue-by-issue” approach to a broader integrated water management framework is highlighted.

Keywords: water reuse; history of water reuse; Greek historical data; advances of water reuse; DPR; IPR; integrated water management; reuse conflicts



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1. Introduction

By studying the past, we learn about the present and the future.

Andreas N. Angelakis

Based on the above quote, it should be pointed out that wastewater reuse has a long history, which begins even before proper treatment was adopted. Reuse practices evolved through different development stages in time, with regards to process knowledge, treatment technologies, and the evolution of traditions, regulations, and/or guidelines. Since prehistoric civilizations, progressing to Hellenic and Roman civilizations, reuse became a common practice serving irrigation and fertilization purposes [1]. After a period of neglect, wastewater reuse practices continued to evolve after the 16th century and, despite their decline in the first half of the 20th century, reuse became again popular, mainly in areas with water scarcity problems (mainly in southeastern Greece) [2,3], but also as a means to implement recent concepts about the circularity of resources [3].

Water scarcity and droughts are likely to become more severe and more frequent due to increasing anthropic pressure and observed climate variability: already, in recent years, droughts have considerably increased in number and intensity in the EU area, affecting an estimated 11% of the population and 17% of the territory [4]. Greece and other countries

in the Mediterranean region are considered to be among the world's most water-stressed regions, as highlighted by the 2030 estimates of the water exploitation index (indicative of “water stress”) released by the European Environmental Agency (Figure 1) [5].

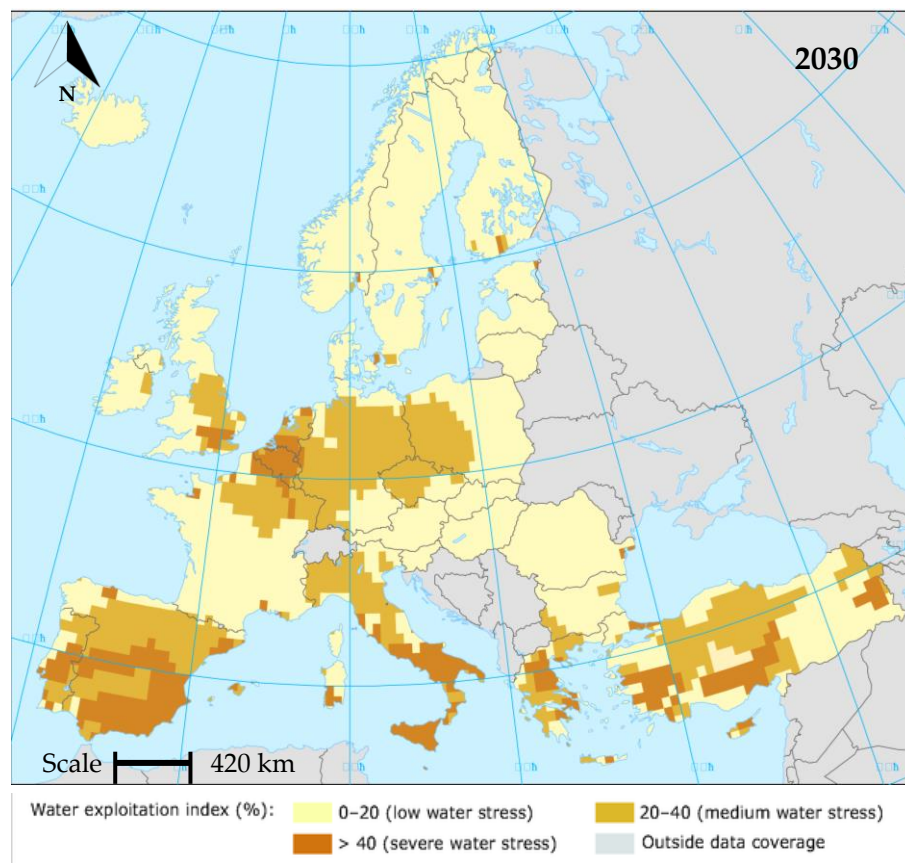


Figure 1. Water stress 2030 forecast for Europe (Source [5]).

Water stress is caused by over-abstraction and overuse of a finite resource; the main pressures on water resources are exerted by irrigation, which, on global average, accounts for about 70% of freshwater resources use (just over 51% as EU average), with about 24% consumed by urban demand followed by the power and industrial sectors. Reduced availability of water resources is also caused by pollution of surface and groundwaters. A peculiar problem in the Mediterranean region is given by tourism, which could cause significant stress in areas with already limited water resources (e.g., popular destination islands in Greece, Italy, Spain, and elsewhere).

Wastewater is the only remaining potential water source bound to increase as the population grows and consumes greater amounts of water. Treated wastewater could hence be considered a reliable supply source, largely independent from seasonal droughts and weather variability. Wastewater was viewed throughout millennia as a resource that must be recovered and considered part of the available water budget. The United Nations (UN) [6] has defined wastewater as a yet untapped available water source; the global transition to Circular Economy [7] could be supported by improving wastewater treatment and increasing reuse, as called for in Sustainable Development Goals Target 6.3 (Clean Water Sanitation).

Due to climate variability and increasing drought phenomena in the climate-vulnerable areas of the planet (e.g., the Mediterranean basin), the use of reclaimed wastewater poses a valuable option, at least for crop irrigation to support crop production and the agricultural economy. Indeed, in the Mediterranean region reuse of treated wastewater is increasing: in Jordan and in Israel, about 90% and 85% of wastewater is currently reused for agricultural irrigation, respectively [8]. It is estimated that treated wastewater could already replace

about 12% of freshwater used for agricultural irrigation globally [7]. If treated wastewater was recognized as part of the hydrological cycle and managed within the integrated water resources management (IWRM) process, this would contribute to meeting the water requirements and accepting the “one water” concept.

In modern times water quality monitoring has much evolved from the past [9]; new contaminants have been identified, and water quality standards for pollutants are well-defined and more stringent. As a consequence, the technologies for wastewater treatment must necessarily keep up with all possible reuse expectations. This is mainly applied to the developed countries that can undertake this process. Unfortunately, developing countries cannot have this ability, and this is why the Food and Agricultural Organization of UN (FAO) and the World Health Organization (WHO) have less stringent water quality standards that do not focus solely on wastewater quality but on other measures such as immunization, types of irrigation, etc.

Historically, in Greece and other countries with low water availability, wastewater derived from wastewater collection systems has been the principal source of reclaimed water. However, population growth and urbanization, combined with limited reliable water resources, have also contributed to the consideration of a wider range of potential water sources for reclamation and reuse. Since the beginning of this century in Greece, small and decentralized wastewater systems have increased and in the future, the potential for wastewater management systems and reclamation and reuse should be improved.

This paper presents an overview of water reuse in Greece, stemming from the premise that we study history not to learn about what happened in the past but to understand the present and to trace the future. It is organized as follows: Section 1, the prolegomena, is an introduction to the theme and elements (e.g., water scarcity, wastewater management history, the present, and the future) of the review; Section 2 discusses our methodology; Sections 3–5 explain the distinct phases of water reuse from the prehistoric era to early and mid-modern times; Section 6 is dedicated to present-time wastewater reuse in Greece; Sections 7 and 8 refer to the challenges, future trends, and integrated management of water reuse, mainly in Greece; and finally, Section 9 is the epilogue that includes conclusive remarks and highlights.

It should be noticed that in the first section, we are situating our study in the long history of Greece. Moreover, Greece is a problematic country regarding water reuse. For example, the construction of the biggest Wastewater Treatment Plant (WWTP) of Athens—the capital of Greece, with a capacity of more than 300 million m³/yr—on a small island prohibited the reuse of the treated effluent. The treated effluents are disposed of in the sea. Only a very small part is reused for green irrigation on the small island. In addition, the European Union (EU), in the contemporary era, is somewhat behind the developed world on water reuse; thus, a few examples from other places are implemented.

2. Research Methodology

The research methodology included: (a) visits and explorations of the archeological places in Greece; (b) comments and exhibitions available on the Internet; (c) a thorough review of the available literature based on the objectives of the study; and (d) communication with water supply and sewerage municipal enterprises and companies. Photos have been occasionally taken directly from these places and the majority were collected from the literature review. The major historical periods examined in this study include prehistoric times (ca 3200–1100 BC), historical times (ca 1100 BC–476 AD), medieval times (ca 476–1400 AD), early- and mid-modern times (ca 1400–1900 AD), and contemporary times (ca 1900 AD–present). Furthermore, the status of water reuse in Greece, water reclamation and reuse trends, and challenges and future trends in integrated water and wastewater management are thoroughly examined and discussed to highlight the potential issues and challenges. Emphasis has been given to modern technologies of water reuse application, on understanding and quantification of reuse, and on the development of water reuse criteria, guidelines, and regulations, given their importance in the design and application of water reuse practices. Before the epilogue, the case of Attica is presented and discussed.

3. Water Reuse from Prehistoric to Medieval Era (ca 3200 BC–1400 AD)

3.1. Prehistoric Times (ca 3200–1100 BC)

The first evidence of the use of wastewater for agricultural irrigation and fertilization dates back to ca 5000 years ago, during the Bronze Age of Minoan and Indus Valley civilizations [10]. Advanced drainage and sewerage systems were developed by Minoans for disposing of wastewater to rivers (e.g., in Knossos palaces) or to the sea (e.g., Zakros palace) and/or to agricultural land (e.g., Phaistos palace and Villa of Hagia Triada). In the Palace of Phaistos, the outlet of the wastewater/stormwater drainage system (Figure 2a) was used to divert this stream to the nearby farmland (Figure 2b). A section of the sewage and stormwater drainage system of the Villa of Hagia Triada is shown in Figure 2c; one of the cisterns used to collect and store this flow onsite for agricultural uses (Figure 2d).



Figure 2. Water reuse in prehistoric times: (a) drainage channels in the palace of Phaistos and (b) downhill farmland irrigated by the flow; (c) drainage channels in Hagia Triada and (d) cistern in Hagia Triada for storage of water targeted for land application (Photos are of Andreas N. Angelakis).

The villa of Hagia Triada and Phaistos probably had the most advanced ancient Minoan drainage system. This system was admired by several visitors, including the Italian writer Angelo Mosso [11], who visited the area in the early 20th century. During heavy rain, he noticed the still-perfect functionality of the system, and commented: “I doubt if there is another case of a stormwater drainage system that works 4000 years after its construction.” The American writer Harold Gray [12] similarly said: “Perhaps we also may be permitted to doubt whether or not our modern sewerage systems will still be functioning after even one thousand years.” Minoans planned and constructed installations that functioned for centuries, unlike today, when a project is considered satisfactory if it operates well for 40–50 years [13].

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

In practice, all water on the planet is continuously reused and recycled and reused in an endless cycle. The Ionian philosopher Anaximandros (ca 610–547 BC) was the first to refer to meteorological phenomena, hydrological processes, and, broadly speaking, to water recycling: “Rains are generated from the evaporation (*atmis*) that is sent up from the earth toward under the sun” (Hippolytus, Ref. I 6, 1-7-D. 559 W.10). Thereafter, Aristotle (384–322 BC) referred to the water phase change: “The sun causes the moisture to rise Even if the same amount of water does not come back every year and in a given place, yet in a certain period all quantity that has been abstracted is returned” (ibid, II.2, 355a 26) [14]. He also reported that “Salt water when it turns into vapour becomes drinkable [freshwater] and the vapour does not form salt water when it condenses again; this I know by experiment”. (*Meteorologica*, II 3). However, the balance of the natural hydrological cycle has been disturbed due to the explosion of the global population, which, in turn, has led to an ever-increasing demand for water. Thus, nowadays, water resources are exploited at a rate that exceeds their natural regeneration rate.

Ancient Greeks continued the Minoan tradition of wastewater reuse in agriculture at a larger scale [10,15]. During the Classical and Hellenistic periods, wastewater and stormwater were removed by city-wide drainage and sewerage systems dug in lateral streets between houses. An ancient drainage and sewerage system was discovered southeast of Athen’s Acropolis, which consisted of a stone central sewer and drain which collected wastewater and rainfall from surrounding houses.

Sewers with larger cross-sections were built of stone in a variety of different ways. In the most sophisticated case, storm water drains are carved of stone exposed like a canal. Two examples are given in Figure 3a, which depicts a drain in the Agora of ancient Messene in southwestern Peloponnesus, a city built in 379 BC, which was known for its walls, the best preserved in Greece and the strongest in antiquity [15]. Moreover, the great drain and sewer under the Agora in ancient Athens delivered a mix of runoff and wastewater into a large collection basin (Figure 3b) [16], from which they were directed to the agricultural fields located in the downhill areas—which, nowadays, are known as *Elaionas*—through brick-lined conduits [17]. Similar systems were found elsewhere; for example, in the hill of Pnyx, where a series of drains were unearthed during archaeological excavations [18]. Throughout the ages, human civilizations have paid close attention to wastewater and have reused it in various ways. In arid climates in particular, wastewater would pass through many reuse cycles, a fact attested to by both Classical Greek, Jewish, and Roman literature. Furthermore, unplanned, incidental or de facto reuse of wastewater had a very long history throughout the medieval periods [19].

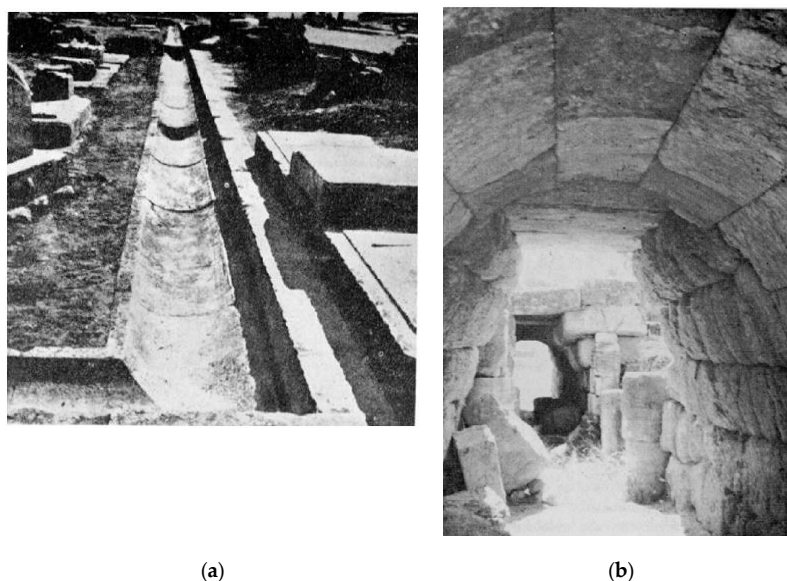


Figure 3. Sewers and drains in ancient Greece: (a) drain in the Agora of ancient Messene; (b) drain and sewer in the Agora of ancient Athens (with permission of Prof. Nikos Mamassis).

3.3. Medieval Times (ca 476–1400 AD)

Romans were excellent hydraulic engineers, as testified by the ancient infrastructure that can still be seen nowadays, sometimes in operational efficiency. Alongside the construction of elaborate aqueducts carrying water for several kilometres, cisterns for harvesting storm rooftop runoff for domestic uses were discovered in Pompeii's archaeological site. In the post-Roman period (ca 476–1400 AD), however, there was no improvement in the methods of waste removal, and little progress was made in water technology and knowledge. Although water reuse persisted in a few places, as testified by the remains of fishponds from the 13th century receiving nutrient-rich wastewater from abbey latrines discovered in Germany and France, sanitation in urban centers mostly reverted, at best, to basic practices. Lack of sanitary precautions resulted in outbreaks of infective disease [20]. As urban populations expanded, the disposal of human excreta, largely unregulated, became a critical issue in large cities. For example, in Paris, property owners were required to provide new dwellings with onsite cesspools only in 1530 [21]. Residents were willing to pay only for their neighborhood sewers, often discharging into the next one [21]. This vision, a sort of NIMBY approach for the times, was exported to Australia and the Americas, which were discovered and populated by European immigrants.

4. Early and Mid-Modern Times (ca 1400–1900 AD)

During this period, concerns regarding water and health issues were gradually developed. During the Renaissance (ca 15th–17th centuries), sedimentation tanks and soil filtration systems were introduced. In mid-1800 “sewage farming”, a modern, slightly cleaner version of the ancient Greek wastewater disposal system became relatively common in England and other European countries, and into the 1890s, land treatment systems (LTS) use was extended to Mexico and Australia. Thereafter (from the beginning of the 20th century), LTS were adopted in the USA and Europe, including Greece. In 1914, sanitary engineers, E. Arden and W. T. Lockett from the River Committee of the Manchester Corporation, discovered the principles of the activated sludge process [22]. This opened the way for the separate reuse of low-organic-load treated effluents and biosolids.

5. Contemporary Times (ca 1900 AD–Present)

After the Second World War, significant technological innovations in wastewater management were developed, such as the first WWTPs, which were able to handle large flows and make effluents suitable for direct discharge into waterways and to the sea. These plants were widely adopted by major urban centers around the globe as they required smaller areas for treatment compared to sewage farms [23–25]. The 700,000-inhabitant capacity, sedimentation-only plant in Bubeneč (Prague), built in 1900–1906 as a completion of the new sewerage system, is regarded as the first modern facility of the type. Treated effluents and solids residues were then applied separately to agricultural land. The Jones Island WWTP in Milwaukee was the first large-scale biological treatment facility in the USA, built in 1926. Effluents were disposed of in Lake Michigan (from which the city draws its potable supply) and process residues (biosolids) were sold after processing as a brand-name fertilizer.

Since the beginning of the 20th century, the concepts of wastewater reclamation and reuse, as well as resource management, started to be promoted. Some contemporary examples of treated effluents reuse for agricultural irrigation include reclaimed water from the Nosedo WWTP in Milan (Italy)—opened in 2003 with a capacity of 1.25 million population equivalent (p.e.)—being used to irrigate over 100 km² of agricultural land adjacent to the city. Imposing facilities have recently been purposefully designed for effluent reuse in dry Mediterranean countries; the Bahr El Baqar WWTP in Port Said (Egypt), inaugurated in 2021, is the largest of its kind worldwide—with a daily treatment capacity of 5.6 million m³/d—specifically designed to treat water that will be transferred to the North Sinai region for the reclamation of agricultural land. Another massive WWTP is scheduled for completion in 2023 in the Hamam District in western Egypt (the New

Delta WWTP), with a 7.6 million m³/d capacity, the effluents of which will serve to reclaim agricultural areas east of the Nile's delta area.

In the meantime, a variety of criteria for the reuse of reclaimed water for crop irrigation and other beneficial uses were developed and adopted, primarily to protect public health and water resources. In England in 1912, the “Royal Commission on Sewage Disposal” adopted for the first time standards regulating the discharge of the effluent, introducing limitations of BOD and suspended solids at 20 and 30 mg/L, respectively [26]. A few years later, in 1918, the California State Board of Public Health introduced regulations covering irrigation with sewage effluents. Nowadays, rules and regulations exist in several countries regarding the use of reclaimed water. These are discussed in Section 7.3.

Nowadays, most reuse applications are related to irrigation. Non-potable uses in urban areas may include reuse for toilet flushing, fire-fighting, car washing, street washing, and non-irrigation landscape improvement (e.g., urban lakes and ponds); in non-urban areas, they may also include seawater intrusion barriers in coastal areas and even artificial snowmaking for recreation (e.g., skiing), which may be an efficient alternative to irrigation in the non-growing season in some locations.

Potable reuse is emerging as the leading application sector in terms of technological innovation in water management. Indirect potable reuse (IPR) refers to treated water discharge to the water surface and subsurface water reservoirs, which provide natural residual pollutants degradation and long-time buffering and mixing before treatment, mimicking the natural cycle. Direct Potable Reuse (DPR) refers to the introduction of purified water into potable water distribution networks or raw water supply short-term retention sources (e.g., service reservoirs) immediately upstream.

Health protection concerns, initially focusing on microbiological aspects, have extended to a comprehensive assessment of chemical quality, particularly concerning “emerging” contaminants [27]. Water reclamation technologies have been greatly improved and diversified in parallel to advances in drinking water research [10,28]. Applications and examples of water reuse worldwide are given in Table 1.

Table 1. Water reuse cases around the globe [7–30].

	Region	Countries	Reuse Volume (km ³)	Applications	Examples
1.	North America	USA, Canada	9.2	DPR IPR Recreation Environmental Irrigation Municipal Industrial Various reuses	Orange County; Big Spring, TX, and Nevada; Arizona, Pomona, Los Angeles, CA, and Nevada; Commercial buildings in British Columbia and Toronto Healthy House; Refineries, Power plants Monterrey, Nuevo Leon, Mexico
2.	South America	Argentina, Brazil, Chile, Colombia, Mexico, Peru	2.1	Irrigation Municipal	Mezquital Valley and Caribbean Islands; Road and monuments washing in Sao Paulo and Fortaleza, Brazil
3.	Europe	Spain, Cyprus, Germany, Belgium, Malta, Greece, Italy, France	6.7	Environmental Recreational Agricultural	Aquifer recharge; Golf course irrigation; Sant Antonin sewage treatment plant (Malta)
4.	Middle East and Africa	Israel, Egypt, Namibia, Kuwait, Tunisia, Ghana, Ethiopia, Saudi Arabia, Jordan South Africa,	7.7	DPR IPR Irrigation	Windhoek (Namibia); Tel-Aviv, Dan region; Agricultural and landscape irrigation in Tunisia; Durban Water recycling plant, South Africa
5.	Asia Pacific	Japan, China, India, Hong Kong, Singapore, South Korea, Australia	15	IPR Municipal Agricultural Industrial Recreational	NEWater Singapore; Toilet flushing (Shinjuku, Tokyo, Kitakyushu, and Tokai regions); Virginia Pipeline Project Adelaide, Australia; Oil refineries in Geelong (Victoria); Kwinana Water Reclamation Plant
6.	Russia	Moscow, Vladivostok, St. Petersburg	1	Industrial	Oil Refineries

Water reuse is a priority in the Strategic Implementation Plan of the EU's IPW (Innovation Partnership on Water), and its maximization is a specific objective addressed in the document "Blueprint to safeguard Europe's water resources" [31]. Water reuse projects for irrigation, industrial uses, and aquifer recharge have been initiated both in southern (Spain, Italy, Greece, Malta, Cyprus) and northern (Belgium, Germany) EU countries under different climatic conditions. Today, about 1 billion m³/yr of treated urban effluents are reused in the EU; this represents less than 0.5% of freshwater withdrawals. However, the reuse potential in the continent, is much higher, it is estimated at 6.7 billion m³/yr. In addition, the cost of freshwater withdrawals is usually higher than treated urban effluent used for production DPR, especially in areas under water scarcity. The area of Thessaly (Central Greece) can be used as an example; it is an area with pronounced negative water balance, where the underground water-table has decreased significantly over the last decades due to over exploitation, and the pumping in the groundwater aquifer has become very costly. Under these circumstances the use of treated water for irrigation and urban use is an economically and environmentally sustainable solution.

Water reuse for potable use has expanded in many areas of the world, e.g., the USA, Australia, Canada, Namibia, and Singapore. DPR in Windhoek, Namibia, has been in place since 1968 in one of the first facilities of this type, producing 21,000 m³/d more recently, it has been adopted in Singapore (600,000 m³/d), and DPR with a planned capacity of 38,000 m³/d is under development in El Paso (TX, USA). Over the past 20 years, Singapore's NEWater project has successfully expanded into a well-accepted approach, able to sustainably meet more than half of the country's water demand [32]. Singapore, the world's most densely populated country (5.7 million people in 720 km²), is practically devoid of natural aquifers, which makes for quite an interesting case of the reuse approach. NEWater, surpassing drinking water standards, is produced by advanced treatment (reverse osmosis, microfiltration, and ultraviolet disinfection) of tertiary effluents from the city's WWTPs. Effluents are discharged into artificial surface reservoirs where they mix with freshwater before being further treated in existing water works with conventional potabilization techniques before distribution. Applications and examples of water reuse worldwide are given in Table 1.

Relevance of Ancient Wastewater Management to Modern Times

To put in perspective the ancient wastewater management principles and practices discussed in this paper, it is important to examine their relevance to modern times and to harvest some of the lessons learned. In general, the ancient water management examples described earlier manifest significant similarities with those of current times [33]. In terms of the evolution of wastewater technology, we are not sure whether it waste derived from ancient Greek technological achievements, or whether Greek achievements were totally forgotten, especially during dark ages, and thus had to be reinvented in modern times [34]. However, according to Koutsoyiannis et al. [13], "bridges" from the past to the future are always present, albeit sometimes invisible in the present. Thus, in addition to many constructions that have been continuously or intermittently in operation up to the present day, written information from ancient Greece has survived.

As has been mentioned above, current-day engineers typically use a design period structures, e.g., sewerage and drainage systems of about 40 to 50 years, which is related to economic considerations. Sustainability, as a design principle, has entered the engineering lexicon within the last decade. It is difficult to infer the design principles of ancient engineers. Nevertheless, it is notable that several ancient works have operated for very long periods, extending contemporary times.

6. Current Status of Water Reuse in Greece

More than 492 WWTPs in Greece produce effluents with high reuse potential countrywide; at present, however, treated effluents are in most cases still discharged into the sea. Notable examples of reuse in Greece are presented in Table 2. Agricultural irrigation

is the main consumer of water in Crete, with about 7828 million m³/yr (~85% of total demand), as a consequence of local hydrological and microclimatic conditions. Treated effluents can be reused to irrigate crops or replenish aquifers and even hinder seawater intrusion [35]—an important option, particularly in more vulnerable areas of Greece such as the southern part and the islands, which suffer periodically from intense water scarcity phenomena [36]; they can also be seen as a potential source of nutrients for crops, reducing the use of industrial fertilizers and thereby their environmental and economic impact [3].

Table 2. Current status of wastewater treatment in Greece (adapted from [37,38] and information provided from Hellenic Union of Municipal Enterprises for Water Supply and Sewage (<https://www.eureau.org/about/members/greece-edeya>, accessed on 15 March 2023).

Population Served (Range)	WWTPs (n)	Capacity (hm ³ /yr)	Reused (hm ³ /yr)	Possible Reuse Type	Comments
<2000	250	8.50	2.80	Agricultural irrigation	Additional small projects (>3300), serving <2000 persons in various stages of planning and development (when completed, they will serve about 22% of the total Greek population)
2000–5000	70	47.00	1.30	Agricultural and landscape irrigation	
5000–15,000	95	167.00	2.50	Agricultural and landscape irrigation and groundwater recharge	Under construction: Palaiochora/Chania, Neapoli/Lasithi, Palaicastro (Sitias)/Lasithi
15,000–100,000	66	320.00	3.00	IPR, agricultural and landscape irrigation, and groundwater recharge	New plants in Koropi-Paiania and Marathon
100,000–150,000	4	30.00	0.75	Agricultural and landscape irrigation	Larisa, Rafina-Artemida, Ioannina, Katerini, Chania
>150,000	7	370.00	0.60	IPR, agricultural and landscape irrigation, and groundwater recharge	Psytalia, Metamorfosis, Thriasio, Patra, Rodos, Thessaloniki, Iraklio, and Volos
Total	492	942.50 ^a	10.95 ^{b,c}		

Note: ^a WWTPs under implementation are not considered. ^b agricultural use is about 1.45% of the freshwater irrigation. ^c About 1.16% of water is now used for agricultural uses.

While water reuse is a high national priority issue, several factors are responsible for the limited use of recycled water in Greece so far. An important factor lies in current national and EU legislations setting strict quality limitations [39,40]. For example, the monitoring of metalloids and heavy metals, with frequency from 2 (<10,000 p.e.) to 12 (>200,000 p.e.) times per year, as well as the monitoring of several organic compounds at least twice/year (>100,000 p.e.), are required. Moreover, EU guidelines set minimum quality requirements for aquifer recharge and crop irrigation [41], and there is the possibility of additional limits for several substances (such as pharmaceuticals, disinfection by-products, anti-microbial resistance genes, pesticides, and others) [42]. Another reason for limited water reuse is low acceptance by farmers and consumers [39,43]; this is mainly related to health risks perception and, in part, to the present pricing policy of fresh and reused sources, which often implies additional user costs for the latter. Potential solutions to overcome these obstacles could be the revision of water quality criteria and/or improved monitoring solutions, new pricing policies for non-conventional water sources, and the application of advanced certification processes [35] compatible with current products and EU policy frameworks [44].

The Case of Attica

The Attica region, with an area of 3808 km², is the most urbanized area in Greece; around 3.9 million people, almost 40% of the total national population, live there, and they

are mostly concentrated in the city of Athens. In the Greater Athens area, there are three biological nutrient removal (BNR) WWTPs: the largest, Psytalia WWTP with 3,500,000 p.e. design capacity; the Metamorphosi WWTP in the northwest (500,000 p.e.); and the Thriasio WWTP, with a design capacity of 117,000 p.e., in the west. Another three WWTPs are constructed or planned for construction along the East Attica coastline (Figure 4).

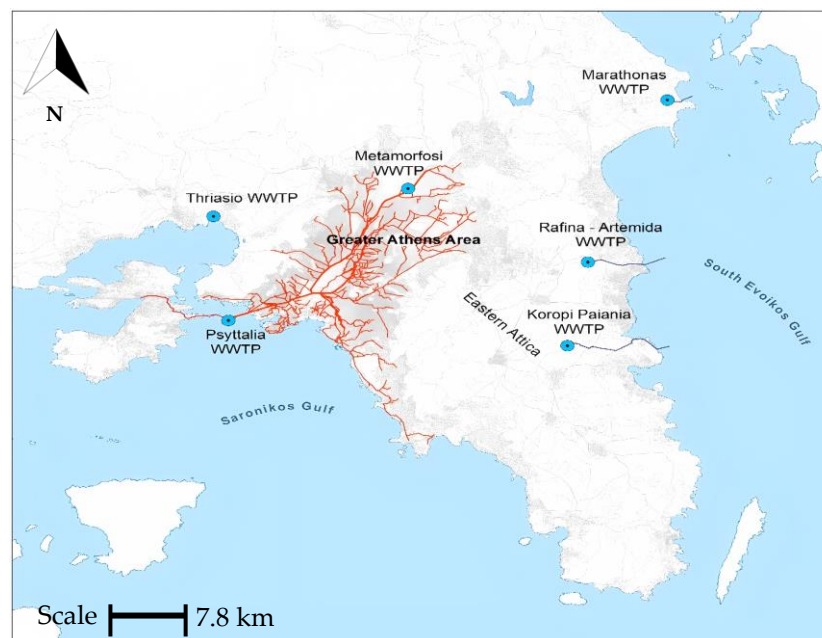


Figure 4. Existing WWTPs and planned with the sewerage network of Attica [45].

The Psytalia island WWTP, started in 1995, with a hydraulic capacity of 300 million m^3/yr , is the largest one in the country, and it includes nutrient removal (advanced secondary treatment) and sludge treatment with the generation of heat and electricity from produced biogas. Three other major wastewater projects are under construction in East Attica for the cities of Rafina/Artemida, Marathonas, and Koropi/Paiania. That of Rafina/Artemida is under construction, Koropi/Paiania has been constructed but the sewerage networks are still under construction, and the Marathonas project is planned. However, these WWTPs are planned to produce reclaimed water suitable for aquifer recharge, restoring the quantity of groundwater bodies. The implementation of the above will be the largest water reuse project in Greece after the one in the city of Thessaloniki in the northern area of the country.

In the future, seasonal increases in the served population due to the expected development of summer tourism could further reduce water availability, especially if combined with the possible onset of drought episodes. It is known that drought periods have always occurred in Greece; for example, in ancient Athens, droughts occurred in the eighth, fourth, second (etc.) century BC and on many other occasions [46]. Thus, potable reuse plays an important role in the development of sustainable water supply augmentation strategies, especially in high-density urban areas such as Attica. The case of Attica shows that water withdrawal from inland areas (up to 220 km away), transportation to cities, treatments, and disposal to coastal waters after a single use is unsustainable [10]. Retrospectively, if the Psytalia WWTP had been built on the mainland with the incorporation of advanced effluent treatment and reuse, Athens could have become a more water-resilient city today.

7. Water Reclamation and Reuse-Trends and Challenges

As seen by the example of the Attica case, planning and design of WWTPs should consider effluent reuse as a standard requirement to optimize final process solutions and outcomes. By properly reusing effluents, the following benefits could be obtained:

- (a) Increased water availability and strengthened adaptation/resilience potential to climatic and/or seasonal variability, especially in vulnerable or water-stressed areas;
- (b) Improved agricultural productivity and improvement of urban green areas management, through fertigation practices (increased water and embedded nutrient supply);
- (c) Quantitative and qualitative protection of available water resources, preventing local over-exploitation and pollution;
- (d) Protection of groundwater resources in coastal areas by contrasting saltwater intrusion in coastal aquifers;
- (e) Increased water systems' energy efficiency and reduction of GHG emissions;
- (f) Fulfillment of water users' expectations by concerted support from concerned stakeholders.

The appropriate understanding of reuse goals, choice of process technology, and regulatory framework are necessary conditions to achieve efficient and effective reuse. These issues are discussed in the subsequent sections.

7.1. Understanding and Quantifying Reuse

Many possible reuse categories exist, which may require specific, further effluent processing [8,47].

In irrigation, reclaimed wastewater can provide simultaneous irrigation and fertilization ("fertigation"). Appropriately treated effluents can avoid excessive nutrients (N, P, and trace nutrients) leaching into groundwater, a frequent consequence of industrial fertilizer use, as such fertilizers are applied in forms that are quickly up taken by crops' root systems. Issues concerning salt, chlorine, and disinfection residuals or heavy metals in reclaimed effluents and their possible accumulation in crops are important and require appropriate treatment or crop management practices (e.g., growth of salt-tolerant crops and disinfection process alternatives to chlorination) [3,47].

Process water reuse in industry is common in petroleum refineries, chemical plants, metal works, pulp and paper industry, laundries, sand and gravel washing, and dust suppression operations. These are generally well accepted because of limited direct human contact and environmental impact. On the contrary, DPR still has limited diffusion, mainly due to acceptance and perception rather than to technological limitations [8,48–51]. In the EU, IPR currently represents roughly 2.3% of reused wastewater, while irrigation, industry, and non-potable applications represent 52, 19.3, and 8.3%, respectively [52]. In India, potable reuse is approaching 15% (Chennai) and 25% of water requirements in Namibia (City of Windhoek) [53–55]. Many examples of DPR and IPR projects have been completed or have been initiated in the USA, Australia, Singapore, and other countries with the support of proper public communication and stakeholder involvement [56].

In Greece, potable reuse could see a potential increase, particularly in areas with severe water scarcity and increasing water demand, such as tourism destination islands [35,57,58] and/or rapidly growing, densely populated urban areas [59].

Safe potable reuse could be achieved by incorporating treatment advances and strict monitoring programs to meet standards for specific pollutants and contaminants [56], as discussed in the following section. Public acceptance should be gained by convincingly addressing sociotechnical, cultural, contextual, and demographic triggers that contribute to the establishment of a general public attitude [60].

7.2. Modern Technology for Water Reuse Applications

Technological progress has brought improved or new processes that may significantly change current water treatment paradigms. In addition to traditional contaminants that are generally well removed by conventional wastewater treatment technology, the spread of new classes of pollutants, the detection of which has been made possible by developments in monitoring and analytical technology [9,61,62], is a critical public health issue of the new millennium and requires the adoption of advanced wastewater treatment technologies [28]. For example, antibiotic resistance genes (ARGs) originated from human metabolism [63,64] are often detected in WWTPs [65] and can be transferred to the environment and hu-

mans [66,67]. Endocrine-disrupting chemicals (EDCs) (e.g., nonylphenol, bisphenol, and triclosan) have been observed in municipal and industrial effluents, biosolids, landfill effluents, and livestock wastes [68,69]. Overall, the biggest current challenge is to ensure efficient treatment methodologies suitable for potable reuse along with the detection, identification, and removal of the pollutants/contaminants (either regulated or nonregulated), even those found at extremely low concentrations in effluents [70,71].

The most significant innovation in water and wastewater treatment in the last 30 years has been the introduction of membrane filtration technologies for applications requiring different levels of purification. Reverse osmosis (RO) can remove ion-size constituents (0.001 μm or less) and is mainly applied in drinking water treatment; nanofiltration (NF) operates at a size of 0.01 μm or less; ultrafiltration (UF) can remove the finest particles down to 0.1 μm , including most viruses; microfiltration (MF) operates at particle sizes about an order of magnitude larger and can remove most bacteria and other pathogens.

Membrane filters can be applied to the treatment of wastewater (UF and MF) or raw water for potabilization and/or desalination (NF and RO), with an exponentially increasing number of applications worldwide. It is estimated that membrane-based facilities for wastewater reuse have approximately reached the same annual capacity as those for desalination: approximately 100 million m^3/d [72]. Wastewater of membrane bioreactor (MBR) MF technology provides a highly polished effluent compared to traditional activated-sludge-type systems, directly suitable for non-potable reuse [73,74]. For higher-level reuse (e.g., IPR and DPR), UF and/or RO tertiary post-treatment is usually applied [8]. Alternative approaches to achieve DPR include Carbon-Based Advanced Treatment (CBAT), involving filtration via biological activated carbon and granulated activated carbon coupled with disinfection via UV or chlorination. The process has recently been tested in the US, with several completed projects in several States [75].

Advanced Oxidation Processes (AOPs) are a class of established processes for the removal of a wide range of pollutants in water and wastewater and the achievement of high-level disinfection [31]. AOPs are based on the dosage of oxidizing intermediates, promoting the in situ generation of strong oxidants to achieve the degradation of pathogens and organic compounds to simple organic molecules and their complete mineralization. These processes include Fenton processes, ozone, ultrasound, photochemical, microwave-enhanced, and non-thermal plasma processes, and can involve the application of catalyzers (e.g., titanium oxide, TiO_2 , or graphitic carbon nitride $\text{g-C}_3\text{N}_4$) [76] to increase process effectiveness. Advanced reduction processes (ARPs), on the other hand, are a class of processes that combine different activation methods (e.g., UV, ultrasound, microwave) and reducing agents (sulfite, ferrous iron, sulfide, and dithionite) to form highly reactive reducing radicals (hydrated electrons, hydrogen, and sulfite radicals) that can degrade oxidized contaminants in solution [77]. Since some CECs can only be removed via reduction reactions, these processes will likely gain greater diffusion in the future [78]; they have been shown to degrade many pollutants of concern, including EDCs and even highly persistent pollutants such as perfluorinated alkylated substances (PFAS) [79,80].

Disinfection is a key process to achieve safe wastewater reuse. Chlorine is the most common chemical available in various forms; however, it may generate harmful organic compounds disinfection by-products (DBPs) dangerous to human and ecosystem health. Alternative disinfectants such as ozone and peracetic acid ($\text{CH}_3\text{CO}_3\text{H}$) or UV-based AOPs have therefore been proposed.

Concerning emerging pollutants/contaminants such as ARGs, different methods have been developed and applied so far, including membrane bioreactors, UV disinfection, chlorination and ozonation, blood alcohol content (BAC), sequential chlorine disinfection, solar photocatalysis, photocatalytic ozonation, and advanced oxidation process (UV/ H_2O_2 or Fenton oxidation, $\text{Fe}^{2+}/\text{H}_2\text{O}_2$) [81,82]; however, the complete elimination of contaminants remains a challenge [83].

Another important issue concerns the energy demand for potable reuse of wastewater; WWTPs are highly energy-hungry facilities [84]; it has been estimated that energy consump-

tion of less than 1 kWh/m³ is achievable for potable reuse wastewater treatment, making it a low-energy option for water supply compared to desalination [51,85]. Sustainable reuse can be achieved by implementing decentralized treatment schemes with the use of natural or hybrid-based systems [86,87]. A recent study examined in detail the possible process technologies capable of achieving fit-for-purpose wastewater reuse [8].

7.3. Development of Water Reuse Criteria, Guidelines, and Regulations

Water reuse is a powerful strategy for enhancing water sustainability and water systems resilience; however, differences and inconsistencies in national and international regulations—and the still-uncertain scientific consensus on approaches for their application—remain a challenge. Additional research and debate on these issues and the potential adverse health effects from exposure to residual contaminants in recycled water are needed to increase public confidence in water reuse.

In the US, reuse regulations exist at the State level for agriculture, urban, environmental, industrial, and potable reuse [29]; in addition, the US Environmental Protection Agency (EPA) has recently updated their water reuse regulations and criteria [88,89]. In the Middle East, 11 out of 22 Arab States (so far) have developed legislation concerning the reuse of wastewater effluents. International organizations, such as the FAO, the WHO, the World Bank, and the ISO, have developed their guidelines which have been adopted by many countries in the absence of their criteria [8]. Regulations and guidelines for agricultural water reuse on a global scale have been presented in recent studies [3,90,91].

Several EU regulations related to water reuse have been introduced in recent years [92,93]. The EU Regulation on “Minimum requirements for water reuse for agricultural irrigation”, approved in June 2020, containing new rules expected to encourage and facilitate water reuse, will apply from 2023 [42]. Concerns about emerging contaminants must be translated into specific measures through the newly proposed urban wastewater treatment directive, the adoption of which is targeted for 2040 [94]. Specific regulations are also being discussed at the EC level. So far, EDCs are covered by “REACH” regulations [95]; efforts aimed to set a comprehensive framework for their identification and regulation are underway. A first watch list, including two endocrine-disrupting substances (beta-estradiol and nonylphenol) in drinking water, was released in January 2022 [96].

Microplastics (MPs) can be carriers of several contaminants [97–99] and are commonly found in WWTPs [100,101] from which they can be released into the environment. MPs could be a threat to biodiversity, ecosystems, and human health [102–104]; however, this particular class of pollutants still needs to be addressed by regulations. A proposal to introduce the monitoring of microplastics in WWTPs was recently released [94].

Water reuse requires a flexible and efficient regulatory framework based on realistic risk assessment, taking into consideration the latest knowledge concerning contaminants’ effects and their possible treatment processes to provide reuse criteria that could address all potential health and environmental risks while avoiding unnecessarily restrictive regulations [39].

Wastewater effluent regulations indicate the inability of EU authorities to adopt a uniform framework for all the countries. The example of the outbreak the *E. coli* O104 H4, which was associated with the exchange of vegetables among EU countries and the lack of appropriate and uniform tools of legislation and control, stresses the importance of common and uniform policies to protect public health and environmental sustainability. The establishment of such regulations and best management practices following the EU Water Framework Directive (WFD) will contribute to: (a) improving the management of water resources and increasing the protection of public health and the environment; (b) setting a realistic framework of reuse criteria applicable to all EU countries; (c) decreasing the cost of effluent reuse projects and encourage the wise management of the water sources; and (d) enhancing the agricultural productivity and the quality of products all over the EU [39].

Finally, in some cases (e.g., EU Mediterranean States), the existing national regulations for recycled water need to be updated in accordance with new knowledge to address realistically the potential risks arising from pathogens and trace organics, thus encouraging water reuse by avoiding unnecessarily restrictive regulations. Angelakis et al. [10] proposed the possibility of establishing criteria via water use category independently of the water source or origin (e.g., the one water concept).

8. Future Trends in Integrated Water and Wastewater Management

A significant challenge for the water sector is the transition to an integrated framework where water issues will be addressed according to a holistic approach considering other sectors of human life. This can be exemplified by considering the UN Sustainable Development Goals (SDGs); the water sector is not only linked to SDG 6 “Clean Water and Sanitation”, but it is also directly and reciprocally affected by others via the so-called Water–Energy–Food Nexus, which represents the interrelated nature of global resource systems. Hence, the water sector is affected, for example, by SDG 2, “Zero Hunger”, through water–food relationships; SDG 7, “Affordable and Clean Energy”, through water–energy relationships; SDG 11, “Sustainable Cities and Communities”, through the appropriate use of water resources in urban areas; SDG 12, “Responsible consumption and production”, through the use of water for productive uses; and SDG 13, “Climate Action”, through the effort to reduce climate effects on the availability of water and reduce the climate footprint of their exploitation (Figure 5).



Figure 5. The impact of the water sector on SDGs. The water sector is associated with a number of the SDGs set out by the United Nations.

An appropriate management model must be supported by coherent legislation; moreover, rules must be realistic and flexible, allowing for consideration of local and regional differences, such as the status of conventional and alternative water resources, soil and climatic conditions, water users’ requirements, and the socioeconomic situation [105]. Competition between ecological and anthropic use priorities, as between water users themselves,

is often a massive challenge [106]. Integrated water management models should include, from a theoretical point of view, at least the following:

- (a) Comprehensive analysis of social, economic, and environmental issues (e.g., economic optimization and improvement of social welfare, water pricing, quality, and quantity), with the support of advanced analytical tools such as decision support systems [107];
- (b) Planning for water distribution networks resilience building to deliver water to users with minimal losses and interruptions [36];
- (c) Efficient monitoring of conventional and non-conventional water resources [35,108];
- (d) Promotion and adoption of efficient water use practices and technologies, supported by specific proactive actions such as motivation campaigns and financial/fiscal incentives [36];
- (e) Definition and exploitation of alternative sources, such as treated effluent and brackish/marginal waters, accompanied by supportive actions and policies, such as pricing and development of specific criteria covering all uses [39];
- (f) Specific actions targeted to the water-energy nexus (neutral or positive energy balance systems operation);
- (g) Consideration of water reuse as a key component of holistic water management in agreement with the “one water” concept and the circular economy process [109];
- (h) Promotion of public/private stakeholders dialogue and facilitation of knowledge transfer.

In Greece, due to the uneven spatial and temporal distribution of water resources, the terrain variability, and the frequent water scarcity situations, there is an increasing need for integrated, strategic water management plans [35]. The current water management plans for the 13 Regional Basin Districts (RBDs) of the country (e.g., the RBD of Crete [110,111]) can provide an essential basis for building long-term strategic integrated plans for integrated water management.

Finally, water reuse research priorities, which have the potential to advance the safe, reliable, and cost-effective reuse of municipal wastewater effluent where traditional sources are inadequate, should be identified. Such research priorities could be: (a) quantifying the extent of de facto potable reuse in EU countries.; (b) enhancing methods for assessing the human health effects of chemicals and unknowns; and (c) analyzing the need for new water reuse approaches and technologies in future cities [39].

9. Epilogue

Water reuse will play a significant role in the development of sustainable future strategies for water resource management. Implementation of water reuse practices in areas with limited surface and groundwater sources can result in a sustainable and reliable system, even with regard to supplying high-quality water to urban communities. Given that the water requirements of cities are greater than the wastewater discharged, DPR will not be a standalone water supply, but it can serve as a highly valuable source of water within a broader, integrated regional water management portfolio [112].

Modern practices of water reuse evolved from ancient examples by necessity and opportunity; the technology is now available to produce water for any possible use, including DPR. New technologies are constantly being developed to enhance wastewater treatment for the elimination of emerging pollutants that could still restrict the wider diffusion of reuse practices. A common EU strategy for general water reuse does not yet exist; however, key developments in that direction are under elaboration. Nowadays, southern European countries are leading in water reuse applications in the continent, even though reuse may sometimes be discouraged by overly restrictive quality criteria which may not be fully motivated by scientific evidence, as is the case in Greece. Regulations reflecting state-of-the-art chemical and biological understanding are needed for sustainable water resources management and water reuse.

In Greece, water management decentralization is still a limited practice; however, local water reuse could be boosted by the ongoing implementation of small WWTPs after the larger urban service areas in the country have been covered. Key recommendations for

furthering the sustainable development of wastewater treatment, reuse, and management include the following:

- (a) Feasibility studies concerning treated wastewater reuse with a focus on local environmental impact issues;
- (b) Full consideration of wastewater as a resource in the overall water budget, especially in urban and peri-urban areas;
- (c) Implementation of integrated water management frameworks for resilient and sustainable water supply, storm, and wastewater management;
- (d) Reuse options should be planned from the design phase of WWTPs, with criteria corresponding to the water needs in the surrounding area;
- (e) Policies, guidelines, and incentives for communities and businesses to encourage the most appropriate and cost-effective wastewater treatment solutions based on local capacities and reuse options should be adopted.

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