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A perspective for the acceptance of water reuse: history of the valorization of wastewater throughout the development of society

Ana Silvia Pereira Santos [a,*], Maira Araujo de Mendonça Lima[a], Mickaela Midon Paixão[a], Eduardo Pacheco Jordão[b] and José Manuel Pereira Vieira [c]

[a] Department of Sanitary Engineering and Environment, University of State of Rio de Janeiro, 524 São Francisco Xavier St, Maracanã, Rio de Janeiro, RJ, 20550-900, Brazil
[b] Department of Water Resources and Environment, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[c] CTAC – Centre of Territory, Environment and Construction – School of Engineering, University of Minho – Campus de Azurém, Guimarães, Portugal
*Corresponding author. E-mail: ana.pereira@eng.uerj.br

ASPS, 0000-0001-7823-9837

ABSTRACT

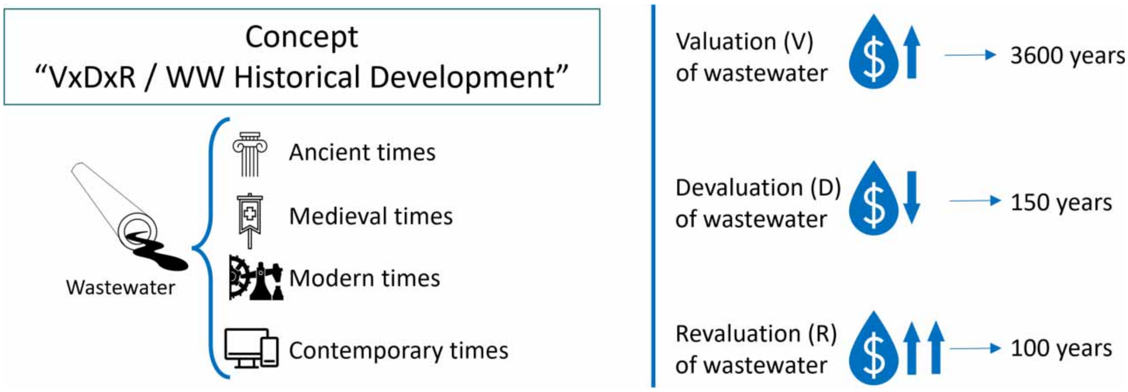
Water reuse has been practiced for more than 5,000 years with different approaches by society throughout historical periods. We developed a concept that presents evidence and artistic-cultural manifestations about episodes of *valorization* (V), *devaluation* (D), and *revaluation* (R) of wastewater (WW) throughout history, called 'Historical Development VxDxR/WW'. We conclude that WW has had a long *valorization* period of more than 3,500 years; the WW *devaluation* period lasted approximately 150 years; and in the last 100 years, there has been an attempt to revalue WW, with scientific, legal, and technological advances. We believe that a broad understanding of this concept can drive a true paradigm shift to guide public policies and appropriate decision-making, in the context of efficient water management. To guarantee a safe, sustainable, and economically viable water reuse practice, it is necessary to develop and implement a regulatory framework that involves, in addition to legal aspects, regional strategic planning and the production of social education instruments for the acceptance of water reuse. In this sense, this concept can pave the way for the necessary and expected advances.

Key words: Circular economy, Development of society, Historical evidence, Rejection of water reuse, Sustainability

HIGHLIGHTS

- Historical knowledge of the relationship between society and wastewater is fundamental to construct a successful water reuse culture.
- Throughout history, the wastewater valorization period is much longer than the devaluation period.
- The valorization of wastewater in society lasted over 3,500 years; the devaluation, 150 years.
- Currently, in the last 100 years, there is a great attempt to revalue wastewater in society.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The development of society is directly related to the geographic distribution of water and its political use (Boccaletti, 2021), and to the use or final disposal of waste/wastewater (Halliday, 2019). Although the current technical-scientific area is fully aware of the benefits of wastewater (WW) for various purposes, society still strongly rejects this product. This is because modern society believes that WW causes disease, is malodorous and, when improperly disposed of, allows the development of an environment conducive to the vector proliferation.

However, current technical-scientific knowledge demonstrates the feasibility of using by-products from WW treatment, such as: (i) biogas, from the WW sludge anaerobic digestion, has a high potential for use as an energy source; according to Pasciucco *et al.* (2023), the use of biomethane to replace gasoline stands out as an important option against global warming; (ii) sludge produced in WW treatment has a high nutritional power for agriculture and may become an important raw material for the sustainable production of fertilizers, with a low carbon footprint (Chojnacka *et al.*, 2023); (iii) finally, the water used to transport wastes, from the point of generation to treatment, can be reused as an alternative and sustainable source of water for several purposes (Santos *et al.*, 2022). This is recycled water or reclaimed water (RW), the main topic of this paper.

In the past, without current scientific knowledge, wastes were used in agriculture, for soil fertilization (Angelakis *et al.*, 2018). Currently, many water reuse plants are already in operation around the world, for agricultural, urban, industrial, and even drinking purposes (Jones *et al.*, 2021; Santos *et al.*, 2022). The evolution of the technical-scientific knowledge allowed and guided the construction and structuring of regulation at a global level, which began in the last century.

Although advances are substantial in relation to water reuse around the world, there are still many challenges to be overcome to ensure a safe and responsible practice. In general, the challenges involving the rejection, regulation and contextualization of the integrated management of different water sources are known (Angelakis *et al.*, 2018; Shoushtarian & Negahban-Azar, 2020; Santos *et al.*, 2022). However, the pressures imposed by climate change have become more evident and dynamic, requiring more forceful actions. Thus, Fernandes & Marques (2023) state that one of the main challenges is to put into practice the theoretical concept of the circular economy, particularly in the water and WW sector.

In this context, there is a tendency to shape more efficient water management, which involves the regular practice of water reuse, in addition to other actions such as reducing consumption, recycling and controlling losses (Fernandes & Marques, 2023). This more efficient water management permeates the difficulty in advancing adequate policies with the involvement of different aspects: (i) legal: adequate regulation; (ii) social: acceptance versus rejection; (iii) economic: pricing; and (iv) environmental: guaranteeing water to users (upstream and downstream) of a basin (Angelakis *et al.*, 2018; Fielding *et al.*, 2019; Santos *et al.*, 2022; Fagundes & Marques, 2023).

It is important to highlight that the term 'water reuse' is more recent than the term 'wastewater reuse'. Indeed, WW is always used (and not reused) indirectly, as it is discharged into water bodies, upstream of communities. Therefore, when the intention is to recover or recycle water from WW, the more comprehensive term is 'water reuse'. In the specific case of agricultural irrigation, when nutrients are used in addition to water for fertilization, the term 'wastewater reuse' is more appropriate. However, currently, the term 'water reuse,' in a broader sense, has been more widely adopted in the context of the direct application of the practice, where water is recycled or recovered from treated wastewater (TWW). Furthermore, the term 'wastewater reuse' may contribute to the rejection of the practice, while 'water reuse' may enhance its acceptance.

The article highlights the evolution of the relationship between society and WW, from ancient to contemporary times. In this sense, the text was constructed based on a historical timeline. Posteriorly this introduction, item 2 contextualizes water reuse in different countries. Item 3 presents the concept developed in the research that involves the valorization, devaluation and revaluation of WW throughout the development of society. Item 4 presents historical facts and artistic-cultural manifestations divided into four major periods: (4.1) Ancient Times, (4.2) Medieval Times, (4.3) Modern Times, and (4.4) Contemporary Times. Finally, item 5 presents the main conclusions of the study.

In this sense, the study aims to contribute to a broader understanding of a relationship between human beings and WW as a tool for building a real and successful water reuse culture in a global level.

2. WATER REUSE

Faced with advances in water stress, imposed by climate change and population growth, especially in arid and semi-arid regions, the management of water resources has become increasingly complex. In this sense, water reuse can be an important management tool, in the concept of CE, aligned with sustainable development.

Currently, many countries in the world present important advances in the institutionalization of Water Reuse from TWW, with specific characteristics related to their regional scenarios and climate contexts:

- Israel: According to Marin *et al.* (2017), the country uses almost 90% of its TWW for agricultural purposes, thus reaching 40% of its water demand for irrigation.
- China: According to Hu *et al.* (2021), the country has been making major investments in water reuse, increasing from a total volume of approximately 7 billion m^3/year in 2017 (Liao *et al.*, 2021) to over 12 billion m^3/year in 2019 (Hu *et al.*, 2021).
- United States: Since the early 2000s, the country has used approximately 10% of its TWW (more than 13 billion m^3/year) in several applications (Diemer, 2007), has already more than 50 potable reuse plants (direct and indirect), planned and constructed (Mukherjee & Jensen, 2020).
- Singapore: According to Lim & Seah (2013), the country has an extensive diversification of its water sources, considering local collection, imports from the Johor region (Malaysia), desalinated water and RW. Until 2018, NEWater (RW produced by PUB – Singapore's National Water Agency) had met around 30% of the country's water demand; it currently attends 40% and, in the future, it is expected to attend 50% (Santos *et al.*, 2022). According to Lefebvre (2018) NEWater production exceeds 80 million m^3/year.
- Australia: Due to its climatic conditions, the country has been investing in potable reuse, and was the first in the world to publish legal guidelines for potable reuse, in 2006 (Khan & Anderson, 2018). The two main potable

reuse plants in operation in the country (Perth and Western Corridor), have together a production capacity of more than 1 billion m^3/year of RW (Khan & Anderson, 2018).

- Namibia: The country features the oldest direct potable reuse plant in the world (since 1968), with a maximum capacity of 21,000 m^3/day (Wallmann *et al.*, 2021). Currently, more than 400,000 inhabitants in Windhoek are supplied from direct potable reuse (Lahnsteiner *et al.*, 2018).

All countries mentioned are prominent regarding water reuse and consider different characteristics, which are summarized and presented in Table 1. **Israel** is in a semi-arid region, and water reuse is a fundamental condition for establishing its agricultural production. **China**, with an intense economic growth program, uses RW to minimize the risk of water shortages in its industrial sector. The **United States**, with non-potable reuse already institutionalized and established, currently encourages potable reuse in several states, including the publication of guidelines at the national level. Regarding potable reuse, **Australia** provides resources and technical-scientific knowledge for this purpose to guarantee human supply in situations of more severe droughts. **Singapore** has ensured its water independence from Malaysia based on a robust water reuse program, initially for human supply purposes and currently, with greater production for industrial purposes. Finally, **Namibia** has been practicing direct potable water reuse for more than 50 years.

In general, according to Jones *et al.* (2021), approximately 50% of the potable water generated is treated and 11% is reused in a planned manner. It is observed that countries in more severe situations of water stress, such as Israel, Singapore, and Australia, have high percentages of water reuse in relation to TWW. Countries like the United States and China, the two largest economies in the world, have chosen the production of water from alternative sources, with high absolute values in relation to the others. Most of the RW in the world is used in agricultural irrigation, although potable reuse has already been successfully practiced. However, only Namibia, South Africa, and the United States have direct potable reuse plants currently in operation (Santos *et al.*, 2022).

Although water reuse has advanced in numbers, there are still some complex strategic and logistical gaps to be overcome. Fagundes & Marques (2023) highlight the task of defining specific pricing policies, as the rules applicable to drinking water and WW tariffs may not be suitable for this market. These issues consider local specificities (environmental conditions, institutional arrangements, and technical and economic aspects), which make it difficult to transfer experiences between countries and, consequently, decision-making.

However, Santos *et al.* (2022) point to the definition of adequate regulation to involve aspects that allow progress in a safe way and guarantee legal, economic, technical, social, environmental and health viability.

Faced with the worsening drought scenarios, the consolidation of the water reuse practice in a safe, responsible, and planned manner may be one of the joint solutions for more efficient water management globally, including as a driver of the economy (WE, 2020).

Although the benefits of water reuse are consolidated in the scientific community, its institutionalization still faces serious challenges to be overcome, even in the regions most affected by water scarcity (Angelakis *et al.*, 2018; Santos *et al.*, 2022). Its systematization strongly depends on the engagement of society (Salgot & Folch, 2018). Thus, the development and application of social education actions are considered essential, to minimize the effects of natural psychological rejection of water reuse, both from decision makers, technicians, users and the civil society.

Historical knowledge of the evolution of the relationship between human beings and WW is fundamental for the success of the construction of a real and successful water reuse culture on a global level. This list considers the implementation of sanitation infrastructure, the control of waterborne diseases and aspects related to the water reuse for various purposes. In this sense the present work aims to construct a general understanding of the triad *valorization (V) – devaluation (D) – revaluation (R)* of WW related to the historical development of society.

Table 1 | Characteristics of water reuse context in different countries.

Country	RW rate	Characteristics
Israel	87% of the TWW	**Quality and regulation:** RW for irrigation purposes is produced from disinfected secondary effluent and injected into an aquifer for later use in agriculture. According to regulations (first established in 1952 and updated in 2010), this RW can be used for any type of crop. **Incentive policy:** The water sources available for agricultural irrigation include fresh water, RW, and seawater desalination. According to the water reuse incentive policy, the RW tariff is cheaper than the others, subsidized by the government. The result is a massive increase in the production of unconventional waters (RW since 1998 and seawater desalination since 2006).
China	20% of the TWW in urban areas; 12.62 billion m3 /year	**Quality and regulation:** Over the past 15 years, advanced treatment technologies, such as membrane bioreactors, membrane filtration, and disinfection, have been increasingly employed to produce high-quality RW. The concept of 'fit for purpose' is used to define the production of RW with quality that meets the needs of the intended applications. The regulation, which includes different sources of water, was published in 2002, and specific regulations for water reuse were published in 2008. **Incentive policy:** China has encouraged the use of RW through economic stimuli and other means. The overall target is to achieve water reuse rates of more than 25% in water deficient cities, with more than 35% in the Beijing-Tianjin-Hebei region of China by the year 2025.
United States	10% of the TWW; 13 billion m^3/year	**Quality and regulation:** The state of California published the first regulation in the world, in 1918. Water reuse guidelines for the whole country were established in 1980 (with updates in 1992, 2004 and 2012), by the United States Environmental Protection Agency (USEPA). Currently, the USEPA water quality standards for RW are very restrictive for water reuse. For potable purposes, membrane technologies, combined with chemical processes, chlorination and sand/carbons filtration are adopted. **Incentive policy:** The non-potable water reuse is already a consolidated step in the United States; 28 out of 48 states had adopted specific guidelines for water reuse by 2017. Currently, the focus of public policies and incentives has been on potable reuse, in a direct or indirect way; in this case, 15 states have published regulations for potable reuse, beyond USEPA in 2017.
Singapore	40% of the country's water demand	**Quality and regulation:** The current RW (NEWater) production process is a combination of conventional activated sludge, microfiltration or ultrafiltration, reverse osmosis and ultraviolet disinfection. NEWater has consistently achieved high quality, in compliance with World Health Organization (WHO) and USEPA standards. **Incentive policy:** Indirect potable water reuse has been implemented in Singapore over the last 15 years. The initial plan addressed the production of RW for potable purposes. Currently, the industrial demand for high-quality RW increased, reducing demand for potable water. Large investments were made, in addition to outreach efforts in public education to overcome the psychological problem of resistance from the general public to the RW consumption.

(*Continued.*)

Table 1 | Continued

Country	RW rate	Characteristics
Australia	15% of the TWW	**Quality and regulation:** For the non-potable water reuse, the country has non-mandatory guidelines at national level (published in 1999), to guide the strategic planning of states. For the potable purposes, Australia was the first country in the world to publish the regulation, in 2008. The national water recycling guidelines strongly recommend the adoption of robust multiple barrier systems for water treatment involving potable reuse, with the intention of ensuring water quality and public health. **Incentive policy:** The focus on water reuse is for potable purposes. During the drought of 1997-2010, the government established important initiatives to invest in research and development on potable water reuse. However, the actions declined with the end of the drought. Currently, due to climate change, the government has been investing again, but facing the problem of rejection.
Namibia	400 of 477 thousand inhabitants (more than 80%)	During a severe water crisis in 1968, the wastewater treatment plant in Namibia's capital (Windhoek, with almost 400,000 inhabitants) was optimized to produce high-quality water for drinking purposes. In the 1990s, another severe drought led to the design of a new water reuse facility, which began operating in 2002, increasing the previous capacity. Currently, this new facility called New Gorengab Water Recovery Plant provides water for domestic use, while the first one (WWTP Gammams) produces RW for urban irrigation.

Source: Marin *et al.* (2017), Santos *et al.* (2022), Liao *et al.* (2021), Hu *et al.* (2021), Shoushtarian & Negahban-Azar (2020), Kog (2020), Mukherjee & Jensen (2020), Khan & Anderson (2018), Lahnsteiner *et al.* (2018), Rensburg (2016).
Note: RW, recycled water (or reclaimed water); TWW, treated wastewater; WWTP, wastewater treatment plant.

3. THE CONCEPT 'VXDXR/WW HISTORICAL DEVELOPMENT'

The concept 'VxDxR/WW Historical Development' was conceived on a scientific basis, involving the values (*valorization*, *devaluation,* and *revaluation*) internalized to WW throughout the development of society, based on facts and historical periods and artistic-cultural manifestations in each period.

The historical and scientific aspects, in addition to the cultural manifestations adopted in the construction of this concept, were based on the authors' prior knowledge and academic experience, including the development of their scientific research on this topic, over years and decades. As it is a subjective approach, possible methodological limitations can be highlighted such as the failure to address some historical passages and cultural manifestations. However, it is understood that these possible limitations do not affect the general understanding.

Traditionally, the history of society development is divided into prehistory and history. As the first indications for water reuse only in Ancient Times (Angelakis *et al.*, 2018; Halliday, 2019), the period corresponding to prehistory was not used in the concept 'VxDxR/WW Historical Development'. Thus, the overall period is divided in four major periods: (I) Ancient Times, (II) Medieval Times, (III) Modern Times, and (IV) Contemporary Times. In this sense, the main characteristics of each period and their relationship with the WW are presented in Figure 1 as described in the following.

I. The period known as **Ancient Times** (ca. 3,200 BC–500 AD) lasted around 4,000 years, passing through the birth of Christ, which divides the chronology of human history into 'before Christ' (BC) and 'after Christ (*Anno Domini*)' (AD). Given the profusion of actions related to the sanitary advances of society in this

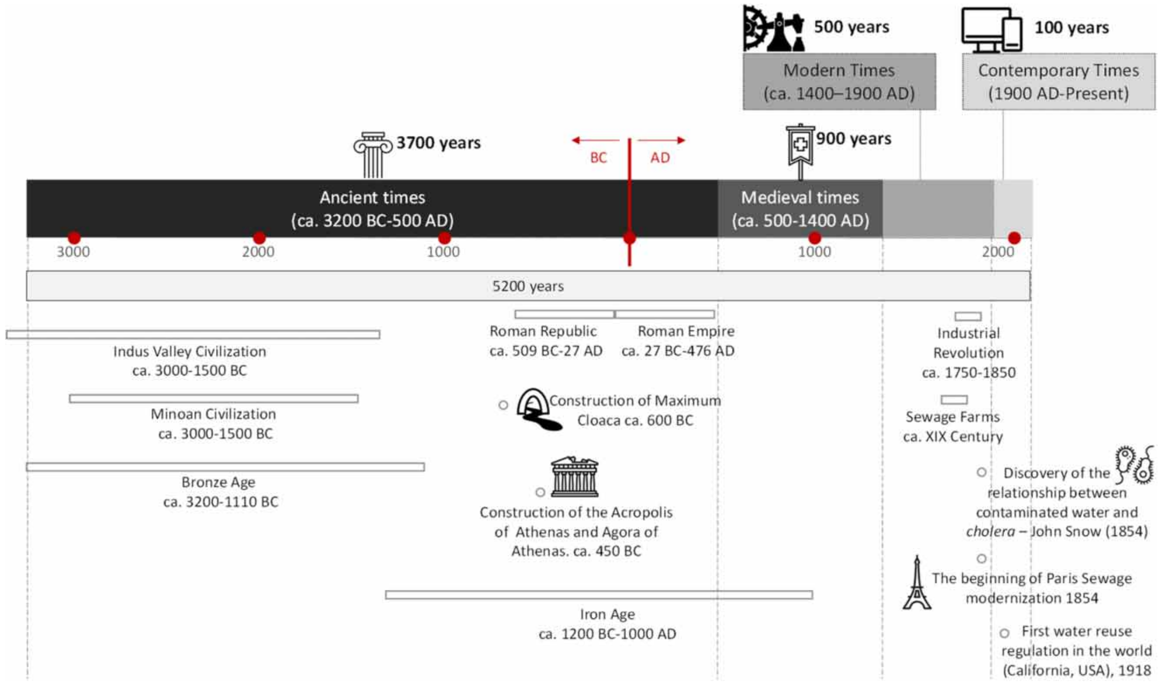


Fig. 1 | Historical periods and relevant facts for the understanding of the concept 'VxDxR/WW Historical Development'. *Notes*: BC, Before Christ; AD, *Anno Domini*.; ca., *circa* (it means around).

period, we divided this period in three sections: (a) The first indications of the use of WW are related to the Minoan and Indus Valley civilizations (Bronze Age), for the purposes of irrigation and fertilization of agricultural land. The Minoan civilization occupied the territory that today corresponds to the island of Crete in Greece; the Indus Valley corresponds today to part of the territories of India and Pakistan; (b) sometime later, some temples in Ancient Greece (Acropolis and Agora) were using WW and rainwater for irrigation and fertilization of orchards and agricultural fields; (c) at the end of the period BC we can highlight the great achievements of the Roman domination period (which lasted around 1,000 years, between Republic and Empire), regarding water and sanitation. Although the main goal of the Romans may be appointed as in relation to their conception and implementation of water supply systems, with emphasis on great aqueducts, it is also important to highlight their systems of waste disposal, having as the main highlight, the 'Cloaca Maxima' (Angelakis *et al.*, 2018; Halliday, 2019).

II. During **Medieval Times** (ca. 500 AD–1,400 AD), Europe was worried with wars and there was little focus on improving water and sanitation services. Rather, what is seen is that all sanitary developments recorded in the Roman period were downplayed and infrastructure was destroyed, due mainly to battles and wars.

III. The **Modern Times** (ca. 1,400 AD–1,900 AD), in its final phase (between the 18th and the 19th centuries), were marked by health concerns, due to the great epidemics that ravaged various regions of the world. In this period, the Microbial Theory tried to gain space in a scientific scenario that still believed in the Miasmatic Theory. The oldest theory (miasmatic) stated that the bad smell (from anaerobiosis hitherto unknown) was responsible for transmission of diseases, while the most modern theory (microbial) stated that diseases such as cholera were transmitted by microorganisms in the contaminated water. During this period, the scientific findings of the Microbial Theory led authorities to recognize the need for clean water and sanitation. The profession of *nightsoilmen*, responsible for cleaning the cesspools of the wealthiest dwellings, gained prominence. Waste from the cesspools was sent do the farms as fertilizer, leveraging the emergence of 'sewage farms' that gained ground all over the world. However, due to population growth as a consequence of the Industrial Revolution, a new interest in more compact WW treatment technologies emerged. It was during this period that the implementation of the world's major WW systems and the lack of interest in the use of WW in agriculture took place (Angelakis *et al.*, 2018; Salgot & Folch, 2018; Halliday, 2019).

IV. In the **Contemporary Period** (from 1,900 AD onwards), significant technological and scientific innovations along with increased deployment of WW treatment plants allowed the industry to handle large volumes of WW for direct discharge into waterways and the ocean. In nearly a century, all understanding of the value (energy, nutritional, water, and financial) of WW has lost strength. However, water reclamation and reuse regained popularity in the 20th and 21st centuries, due initially to (a) natural water management challenges in the most arid regions of the planet; and (b) water challenges related to population growth, megacities urbanization, and climate change. In this context, the first known legislation on the beneficial use of WW was passed in the state of California in the United States of America in 1918 (Shoushtarian & Negahban-Azar, 2020). Since then, nations all over the world, besides global public policy institutions, have tried to recover the value of WW in society, with regulations that guarantee the sanitary safety of the practice and implementation of water recovery plants from treated WW, for various purposes and applications (Santos *et al.*, 2022).

In scale, it can be observed in the schematic drawing of Figure 2 that the *valorization* of WW in society lasted over 3,500 years, considering the Ancient Times (3,200 years) and the first four centuries of the Modern Times; the *devaluation*, which started in the 19th century, lasted until the mid-20th century (150 years); and currently, in the last 100 years, there is a great attempt to *revalue* WW in society. In this understanding, we do not consider the Middle Ages, since in this period there was neither *valorization* nor *devaluation* of WW; the theme was treated with indifference in the face of other objectives of that time.

On the other hand, the artistic-cultural manifestations in each historical period reflect the habits, the way of life, and the social movements that help scientists and researchers to understand the facts and illustrate history. More than that, in general, culture drives the understanding of society, and science bases its decisions on it.

In such a way, in relation to the historical facts and periods, besides the artistic-cultural manifestations, we understand the urgent need to intensify the relationship of the sector with society. Understanding the historical path of the actions that led to the *valorization*, *devaluation*, and the need for *revaluation* of WW empowers society, in the sense of allowing it to actively participate in the construction of this knowledge and reduce the impacts of rejection, known as 'Yuck Factor'. Salgot & Folch (2018) state that end users should be included in decision-making, for a greater chance of success with project implementation.

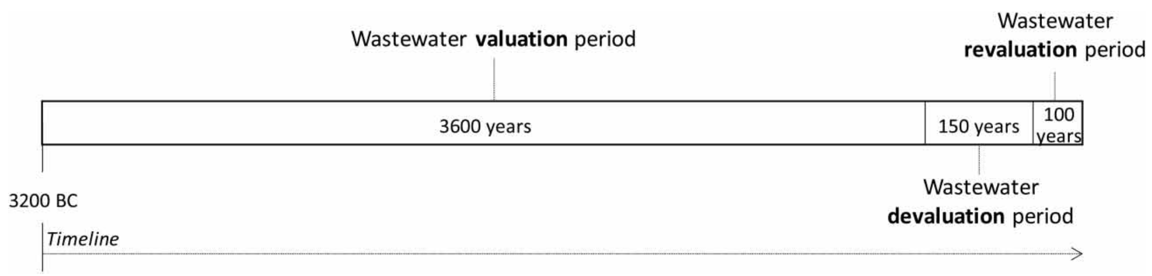


Fig. 2 | Scaled historical representation of periods of wastewater valorization, devaluation, and revaluation. *Note*: BC, Before Christ.

The aim of this paper is to build a general understanding of the triad *valuation x devaluation x revaluation* of WW with the historical development of society. The intention is to contribute with a tool for the purpose of building a society committed to the ***revaluation*** of WW in face of the water reuse practice.

4. HISTORICAL AND ARTISTIC-CULTURAL TIMELINE

This item presents historical facts and artistic-cultural manifestations in the context of the main historical periods reported. They help in understanding the social movements that led to the *valorization* and *devaluation* of WW, as well as the attempt at *revaluation* that follows in the contemporary period.

4.1. Ancient times (ca. 3,200 BC–500 AD)

In the past, the growth of permanent settlements led to the development of WW and rainwater collection systems. The first indications of the use of WW for irrigation and fertilization of agricultural land are from around 3,000 BC, a period that matches with the beginning of the Bronze Age. This scenario can be clearly observed, especially in the Minoan and Indus Valley civilizations.

According to Angelakis *et al.* (2018), the Minoan civilization developed advanced systems for disposing of WW into rivers, the sea, or for routing it to arable land for irrigation and fertilization purposes. The use of WW for agricultural fertilization was adopted at the Palace of Festos (Figure 3) and the Village of Hagia Triada (Figure 4). Figure 3 shows a tunnel at the back of the palace to channel the waste to the fields. Figure 4 shows a cistern used to collect and store WW for later drainage to the fields.

In the Indus Valley, specifically in the cities of Harappa (Figure 5) and Mohenjo Daro (Figure 6), it is recorded that WW and drainage systems have been in use since around 2,600 BC, allowing the development of a thriving civilization in the region (Halliday, 2019).

According to Halliday (2019), in the town of Harappa, all houses were connected to the main sewerage ensuring a proper removal and conduction of WW. From the dwellings, connections, and conduits were interconnected to the main system, reaching rivers, canals, and/or farmland.

In practice, cisterns (seen in Figure 5 as cylinders) were connected to canals in the streets, made of clay and covered with stone, for the conduction of solid waste, mixed with rainwater (Halliday, 2019). This demonstrates the sophistication of the systems, including the fertilizer potential of WW at the time. Removal of the solids deposited in the conduits, for manual application to crops, could be accomplished by removing the stones that covered the conduits.

Although this understanding is not clear from history, it is reasonable to assume that the practice of using WW in agriculture as a fertilizer evolved from the observation that plants grew better where wastes were deposited, either above or below the soil surface.

Later, during the period of excellence of the Roman Empire, human waste was dumped in the streets of the city of Rome, along with other wastes, and even animal wastes and dead animals. This practice left filth all over the city. Thus, the so-called Cloaca Maxima and its channels (Figure 7), a set of underground conduits and interconnections between channels, received rainwater that 'washed' the streets. The main purpose of the Cloaca Maxina was drainage. But as the streets were filthy, this practice ended up washing them and keeping the WW (waste and rainwater) far away from the citizens of the most populous city of that time.

As a curiosity, according to Halliday (2019), the artwork by Giovanni Battista Piranesi (1748–1778), which depicts the Cloaca Maxima (Figure 8) played a relevant role in the education of young people of the English nobility of the 19th century. This work was the most visited on the *Grand Tour* in the 1860s, arousing interest in the technical knowledge behind the art. This artwork is currently on display at the Rijks Museum (Netherlands).

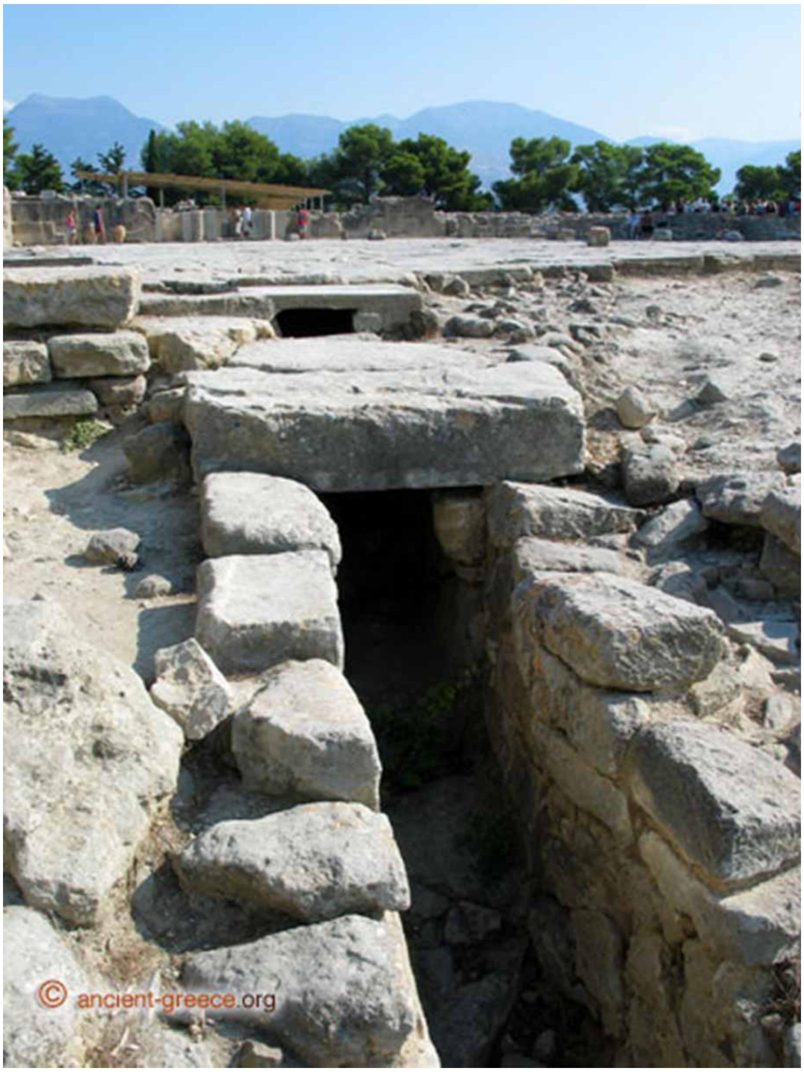


Fig. 3 | Tunnel for transporting wastewater in the Festos palace to agricultural land. *Source*: Angelakis *et al*. (2018).

The *Grand Tour* circuit was a part of the educational process for young European nobles, as a form of supplementary education. Wealthy families would entrust their children to tutors on cultural trips lasting from months to years, with the goal of instilling in them cultural aspects of society. Visits to art museums and other cultural manifestations were then made to develop the youngsters' artistic knowledge.

Another highlight that draws attention to the relationship between the Romans and WW is the worship of the Goddess Cloacina, who represented the Romans' pride in their WW systems (Halliday, 2019). The design of the shrine to the Goddess Cloacina, whose ruins can currently be observed in the Roman Forum, is shown in Figure 9. The worship of the Goddess is also valued with her image minted on coins of the period (Figure 10). According to Boccaletti (2021), Roman coins were minted with the faces of Emperors and Gods. For that society they were on the same level of importance.

Fig. 4 | Cistern in the village of Hagia Triada for storing water and waste for later application to the soil. *Source*: Angelakis *et al*. (2018).

Fig. 5 | Waste transportation system for farmland in Harappa. *Source*: Halliday (2019).

Fig. 6 | System for transporting manure to farmland in Mohenjo Daro. *Source*: Halliday (2019).

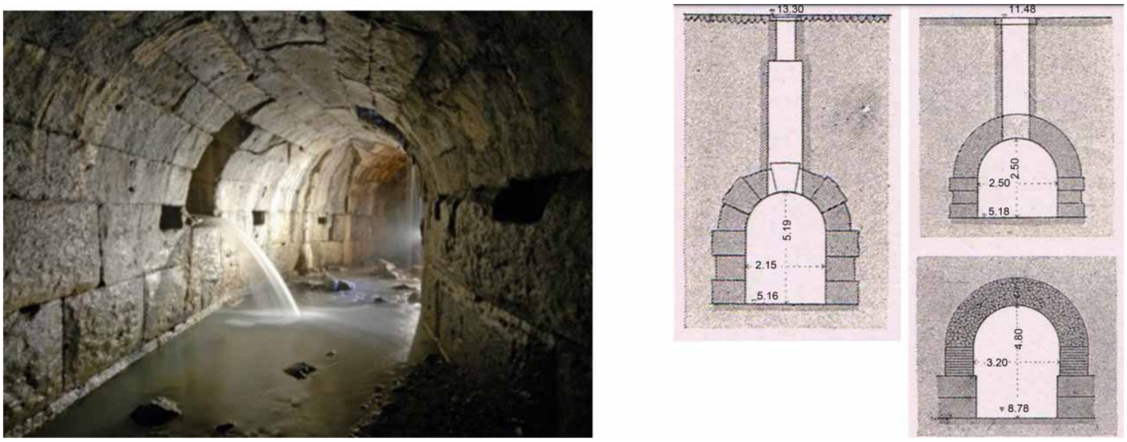


Fig. 7 | Images referring to the Cloaca Maxima in Rome. Left: part of the underground tunnel; Right: cross-sectional views. *Source*: Diamond & Kassel (2018).

4.2. Medieval times (ca. 500 AD–1,400 AD)

In this period, as previously reported, the technical-scientific and infrastructural advances happened almost only in relation to war equipment and similar aspects. Europe was in constant conflict at this time, the main objective

Fig. 8 | Cloaca Maxima of Rome, Giovanni Battista Piranesi. *Source*: Exhibition at the Rijksmuseum.

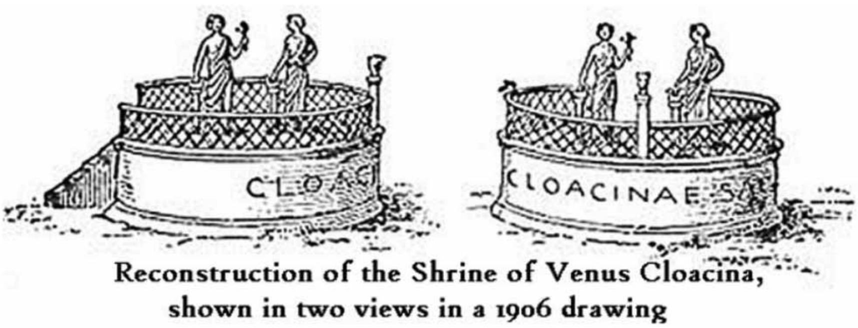


Fig. 9 | Drawing of the Toilet of the Goddess Cloacina, dated 1906. *Source*: Halliday (2019).

being to conquer territories. The water supply, which was quite advanced in the Roman period, suffered a major setback. The new civilizations of the Middle Ages began to collect water from polluted rivers in the cities or from wells dug near ditches and animal dung dumps. The advances of water intakes in rivers with good water quality, even at long distances, were over.

Sanitation services became managed by the population itself, without any quality criteria (Halliday, 2019). Both water and WW lost their value to society, and it is for this reason that this period was disregarded from the concept 'VxDxR/WW Historical Development'. The proliferation of disease marked this period of history, which led to a new chapter in society's development regarding water and WW.

Fig. 10 | Image of the two sides of the Goddess Cloacina coin. *Source*: Halliday (2019).

4.3. Modern times (ca. 1,400 AD–1,900 AD)

The period after the Middle Ages, known as a transition to the Modern Age, was marked by a resumption of interest in sanitary infrastructure. In this period, the occupation of *nightesoilmen* arose, whose task was to clean the cesspools of the wealthier dwellings. The *nightsoilman* usually offered the services of cleaning cesspools, as well as chimney sweeps. The material removed from the pits was disposed of in the river and often sold to farmers for use as fertilizer. Even advertisements for land sales in England showed very high values, stating that the land had been fertilized with WW for many years; in this context, it was considered productive. In Scotland, the land was offered for sale at very high price for the time, based on the assumption that it had received WW for 86 years (Halliday, 2019).

Thus, the concept of sewage farms that used WW as fertilizer was emerging. These farms began to fall into decay in the 19th century as a result of the development of WW treatment technologies for subsequent discharge into water bodies in the post-Industrial Revolution period, which began in the second half of the 18th century.

Still in the 18th century, there was an interesting moment of declared *valorization* of WW by philosophers and political-cultural influencers of the time. The philosopher Pierre Leraux created the so-called *Circulus* doctrine. This was a socioeconomic doctrine that proposed that excreta should be collected by the state as taxes. Although most people did not support the idea or even care for it, Leroux claimed that if people were more educated, then ‘everyone would religiously collect his excrement to give to the State (the tax collector) in place of the personal tax or fee. Agricultural production would immediately double, and poverty would disappear from the face of the earth’ (Halliday, 2019).

Victor Hugo, an important writer and influencer of the time, and a friend of Leraux as well, shared the idea, having written in his most important work, *Les Miserables*, that Paris was throwing 25 million francs a year into the water. Also, the author described the sewers as ‘gold flowing from handfuls,’ making a defense of the doctrine, although he never called it by name (Halliday, 2019; Hugo, 1862 - Excerpt ‘The Intestine of Leviathan’).

Currently, the concept of *Circular Economy* matches the *Circulus Theory*, given the proper proportions, as it associates economic development with more efficient use of resources, prioritizing their reuse. In this context, Sgroi *et al.* (2018) suggest a holistic approach to the sustainable implementation of water reuse, considering political, decision-making, social, economic, technological, and environmental factors, in order to enable a paradigm shift. However, in the literature review carried out by Fernandes & Marques (2023), the authors state that the main motivations for this application are still based on economic, technological, and environmental factors; legal, institutional and political factors still require greater attention. Both Sgroi *et al.* (2018) and Fernandes &

Marques (2023) highlight the importance of this behavioral change for determining new policies, with the aim of boosting more efficient WW management, with a focus on resource recovery.

Although the historical contextualization of the eighteenth century, with the influence of the Industrial Revolution, takes into account mainly the new labor relations and socioeconomic development, as well as the widespread air pollution, it is important to highlight its specific relationship with water. On the one hand, water was the raw material for the generation of hydraulic energy in water wheels, which, although developed in the ancient civilizations of Greece, remained competitive with the steam engine at the beginning of the Industrial Revolution. On the other hand, the increased production of liquid effluents and solid waste from the industrial process strongly contributed to water and soil pollution in an environment already degraded by previous societies.

One might also mention that this period was marked by the disproportionate advance of population growth and mass migrations of rural inhabitants to the cities, in search of new opportunities. Therefore, one may believe that the population increase defined a new path for land use and occupation. The areas available for sewage farms started to disappear, encouraging the search for new WW treatment technologies that would occupy smaller areas.

The population growth and the generalized pollution of water resources, driven during this period, ended up by making the main cities of Europe responsible for the proliferation of the so-called water diseases, generating a great number of epidemics throughout Europe and later in other countries as well. Some artworks from that time presented in Figure 11 show the inappropriate disposal of waste in the environment.

In view of this scenario, it is inferred that, at that particular time, WW started to be seen as a smelly residue and disease carrier. Thus, WW was not seen any more as a potential fertilizer and source of water for irrigation. In this context, the rupture of WW *valorization* stands out, thus beginning a new era of WW *devaluation*.

The beginning of the 19th century was marked by a wide dissemination of diseases and epidemics, such as cholera, which spread through Europe, the United States, and Asia. Initially detected in India, cholera quickly

Fig. 11 | Images of artwork by different artists depict the lack of hygiene of the period. *Source*: Halliday (2019).

reached Europe from merchants who freely transited between these areas and brought with them the cholera vibrio, responsible for transmitting the disease (Halliday, 2019).

In this period, an artistic-cultural manifestation that was gaining momentum (to the present day) was the cartoon, a humorous drawing with a tone of social criticism.

In this context, the illustration by the Austrian cartoonist Frederick Graetz, published in Puck Magazine in 1883 (Figure 12), demonizes the figure of immigrants who brought the disease from Europe to the United States, although the form of transmission was still scientifically unknown. According to Halliday (2019), with the title 'The kind of 'assisted emigrant' we cannot admit,' the illustration personifies cholera as a skeletal invader in the foreground of the drawing; the deadly disease is fought by a series of small figures: a boat representing the Board of Health, cannons loaded with different medicines, and a fragile line of human defenders.

It is noteworthy that in this period, people still believed in the Miasma Theory, formulated in the 17th century by the medical scientists Thomas Sydenham and Giovanni Maria Lancisi. The theory held that diseases were caused by foul smells emanating from the putrefaction process of the organic matter present in the soil and on water surfaces. At the time, the anaerobic biological decomposition process that releases hydrogen sulfide gas, which is responsible for the odor, was not yet known.

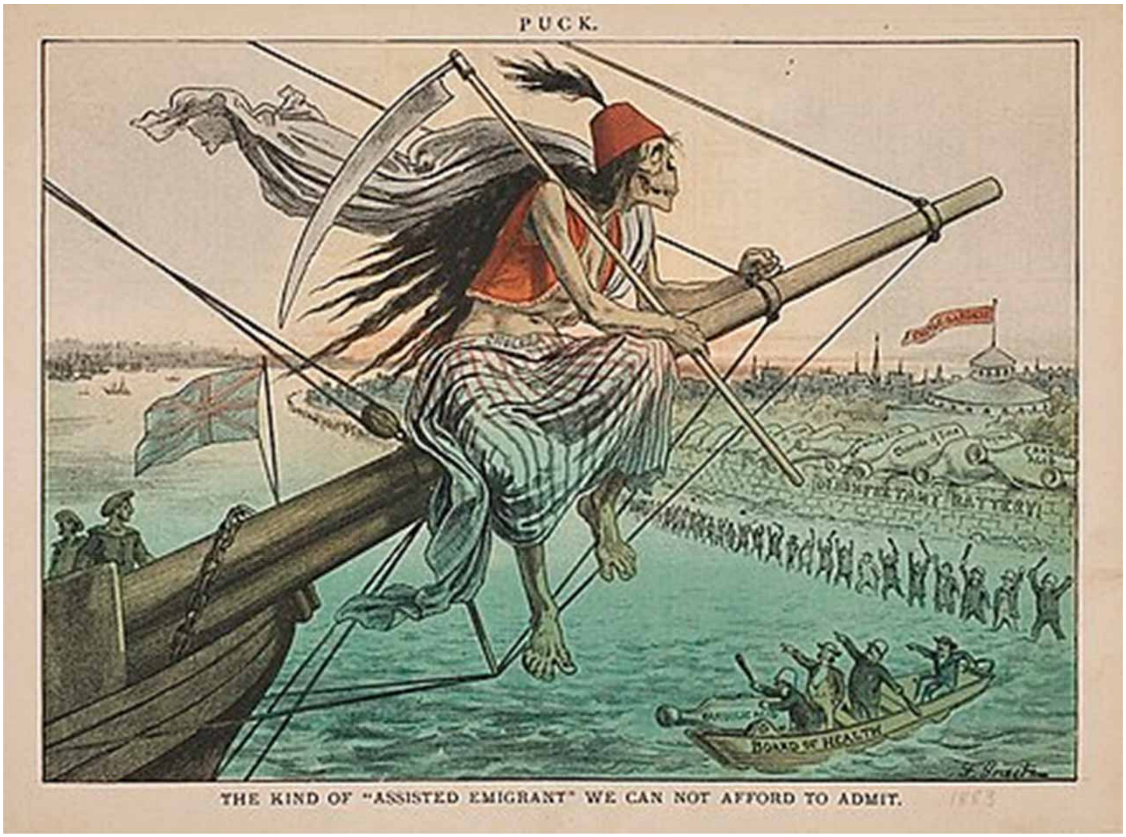


Fig. 12 | Cartoon by Frederick Graetz, published in Puck magazine, 1883. *Source*: Halliday (2019).

Then, in 1849, the medical scientist John Snow, in London, stated that cholera was a waterborne disease, transmitted by contaminated water. However, as already mentioned, the Miasmatic Theory was still predominantly accepted in the scientific community and his Microbial Theory was refuted.

It was only in 1883 that Robert Koch, a German physician, pathologist, and bacteriologist, identified the bacteria responsible for the transmission of the disease, the cholera vibrio. By 1892, in Hamburg, there was already an understanding that cholera was indeed a waterborne disease (Halliday, 2019), as seen in the engraving (Figure 13) that accompanied the headline with the title 'There is Death in the Cup,' published in 'The Illustrated News of the World' on October 8, 1892.

In 1905, Robert Koch, based on the existing knowledge regarding the waterborne transmission of the disease, won the Nobel Prize in Medicine for containing a new cholera outbreak in the city of Hamburg. He advised people to drink boiled water and to use other sources of uncontaminated water. During this period, stations to

Fig. 13 | Engraving 'The Cholera at Hamburg: There is Death in the Cup', published in 'The Illustrated News of the World' in 1892. *Source*: Evans (1987).

boil water were built in public areas, public bathrooms were closed, and the consumption of raw fruit was forbidden (Halliday, 2019).

In 1858, by the time that his microbial theory was effectively validated and accepted, by both the scientific community and public authorities, this pioneer of research and knowledge of cholera, Jonh Snow, had already passed away.

Throughout this period, a new understanding of diseases and WW began, not of the effluent itself, but of the WW collection, removal, and treatment, for the prevention of diseases.

It was at that time, at the end of the 19th century, that Napoleon III looked for the modernization and the urban reform of Paris, together with the city's mayor, Geroges-Eugene Haussmann (Halliday, 2019). One of their major actions, looking for the urban reform of Paris, was the construction of 'Paris Sewers'. The goal was to transport WW away from the people, in order to protect them from contamination and ensure public health.

It is important to highlight that, in this period, the Miasmatic Theory had not yet been replaced by the understanding of the Microbial Theory in disease transmission, as previously reported. Thus, the main intention for the construction of the sewers of Paris, by conducting them to an area far away from the neighborhood, was related to the possibility of generation of bad odors. Only later would the great achievement of this action be understood.

What is interesting is that Napoleon III intended to perpetuate himself in power. In his understanding, one of the ways to achieve his goal was to set out to reconstruct the city, which naturally included water and WW services as an integral part of his plan. Even the unemployed population was used in the infrastructure works (Halliday, 2019).

The story is told and illustrated in the iconic *Musée des Égouts de Paris* (Paris Sewer Museum*)*, which allows tourists, technicians, academics, and students to visit some of the sewer galleries, still operating in the city currently. In the past, as a way to value their work, and consequently the sewer network, the public administration of Paris used to invite the nobility to guided tours of the galleries, in boats pulled by the sewers in the sewage gallery or by wheeled vehicles (Figure 14, left and right, respectively).

The photos in Figure 14 are from 1920 and 1903 (left and right, respectively). Yet, from the 19th to the 20th century, one can notice that a cultural transformation takes place, in relation to the acceptance and even to the existing sewer system. At that time, a new point in the story of WW *valorization* could be seen. This point

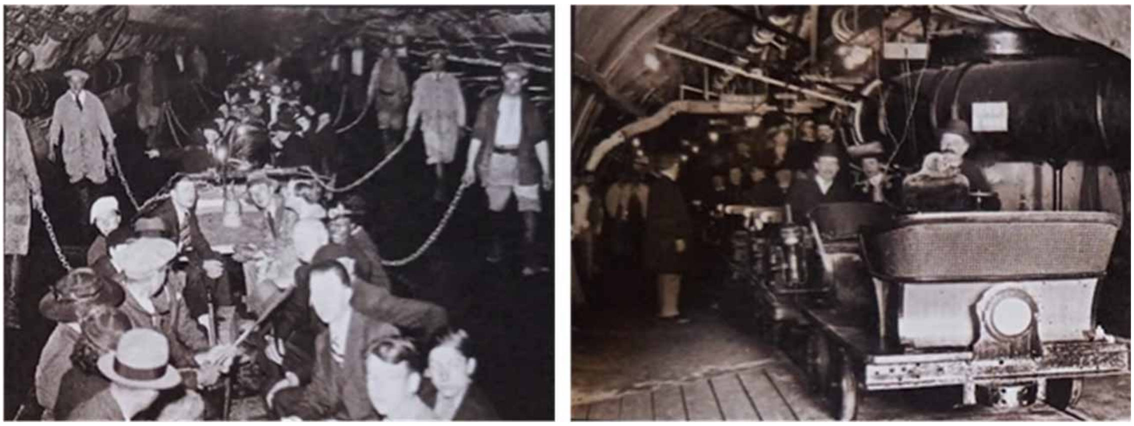


Fig. 14 | Photographs of the noble visitors in the sewers of Paris, in boats (left) and cars (right). *Source*: Musée des Égouts de Paris (Paris Sewer Museum).

was guided by the *valorization* of the infrastructure and engineering works, and not exactly for the fact that collecting and treating the WW is the right way to prevent diseases and a guarantee of a healthy life. Unfortunately, contemporary society has lost any respect or admiration for the service, without realizing that a safe life in modern cities is impossible and unhealthy without WW collection, transportation, treatment, and right final disposal services.

4.4. Contemporary Times (1,900 AD–present)

It can be said that the discussion on water reuse in Contemporary Times starts in the state of California/USA regarding the regulation of the practice in that state. California is a region known for its local water scarcity, and for general approaches to resource conservation and sustainability.

According to Olivieri *et al.* (2020), in 1910, around 35 communities in California used WW for irrigation without any treatment and 24 after septic tanks. WW disposal on sewage farms was accepted as a form of both treatment and final disposal.

Over time, urban areas began to be located too close to the sewage farms and at this point, they gave way to modern WW treatment plants. Actually, there was great concern about odors and health risks associated with the application of raw sewage to the farms. Biological waste treatment technologies, developed between the 19th and 20th centuries (Salgot & Folch, 2018), required much smaller areas and allowed WW to be discharged into the sea, rivers, and streams.

Until the early 20th century, there were no significant regulations or restrictions on the use of WW for agricultural irrigation. As the scientific knowledge of the disease became more widely understood, concerns grew among public health officials about the possible health risks associated with WW irrigation and other non-potable uses of RW. This concern led to the establishment of guidelines and regulations to control the use of WW for agricultural irrigation.

With the understanding that WW could be used as an important and safe soil fertilizer and that, at the same time, it posed serious risks of contamination, the practice had to be regulated. In this context, the state of California published its first regulation on water reuse in 1918. This is the first law regulating the use of WW in the Contemporary Age that is known in the world (Santos *et al.*, 2022). According to Olivieri *et al.* (2020), the evolution of water reuse regulation in California followed the path shown in Table 2.

The evolution of water reuse regulation in California shows the important steps that have been taken toward the *valorization* of WW in the region. Since the regulation of California in 1918, many other countries in the world have followed this example. As mentioned before, Israel introduced its first regulation in 1957 (Santos *et al.*, 2022) and currently uses almost 90% of the country's treated WW, representing 40% of its water demand for irrigation (Marin *et al.*, 2017).

Advances in terms of regulation did indeed happen throughout the 20th century; however, they were very limited to arid and semi-arid regions with experiences of more severe droughts. As shown in Table 2, it is observed that in the second half of the 20th century, the concern about the use of WW in the production of edible crops increased.

In this period, in Europe, according to data available at the Musée des Égouts (Paris), in 1948, one-tenth of the vegetables sold in *Les Halles* in Paris came from sewage farms. However, the procedure was no longer as popular as usual, due to the following reasons: (i) excess WW; (ii) logistical complexity due to the natural seasonality of irrigation; (iii) biological treatment for disposal was gaining more popularity; (iv) new industrial fertilizers helped increase crop yields and competed with urban (sewage) fertilizers; and (v) with suburbs becoming more densely populated, less and less space was given to sewage farms. As highlighted earlier, the 20th century was marked by the decline of sewage farms.

Table 2 | Evolution of water reuse regulation in the state of California, USA.

Year	Action
1918	The regulation defined procedures for the application of raw or septic tank-treated WW for crop irrigation but prohibited the practice for crops consumed raw.
1933	New requirements were added for cross-connection control and effluent disinfection, and the use of raw WW for irrigation of any type of crop was prohibited.
1967	A statewide policy for water reuse was established.
1968	More restrictive criteria were developed for the irrigation of different crops, including landscape irrigation.
1978	More restrictive criteria were defined for landscaping irrigation with uncontrolled access. Also, general requirements were defined for groundwater replenishment by spreading for abstraction for indirect potable use.
2000	Changes in WW treatment and quality criteria were adopted.
2014	Requirements were added for indirect potable reuse of groundwater, supplied with RW by both spreading and injection.
2018	Requirements for indirect potable reuse of surface water were added.

Source: Olivieri *et al.*, (2020).
Note: RW, recycled water (or reclaimed water).

Currently, due to climate change, the widespread pollution of water bodies, and the increase in population, there is a growing interest in the use of treated WW as an alternative source for water consumption. Yet better than saying an 'alternative source', we should say an 'alternative and sustainable water source.'

However, the '*Yuck Factor*' remains an unsolved problem. On the contrary, it is seen as one of the main challenges for the institutionalization of water reuse worldwide (Angelakis *et al.*, 2018; Salgot & Folch, 2018; Santos *et al.*, 2022). It is possible to imagine that during the period of *WW valorization* in ancient times, the acceptance of the practice was high. In reality, the practice was accepted due to a complete lack of knowledge regarding the pathogenicity of WW.

This lack of knowledge among users can be a determining factor in its acceptance. In Namibia, this was the main reason for the non-rejection of direct potable reuse (Fielding *et al.*, 2019). A similar situation can be observed, in general, in relation to *de facto* (unplanned) indirect potable reuse (Angelakis *et al.*, 2018). Users of water supply systems are generally unaware of the source of the water that supplies them. Therefore, they do not suspect its quality, even if the water source presents high levels of pollution due to the discharge of WW upstream.

On the other hand, water scarcity is the main driver of acceptance, according to Duong & Saphores (2015). In this case, users prefer to be supplied by an unconventional source rather than having their water supply interrupted due to scarcity. At this moment, utilities should enhance their awareness campaigns.

Another relevant issue for achieving success in accepting the practice of water reuse is the massive involvement of the government. Campaigns involving public figures lead to greater trustworthiness. This was the case with NEWater in Singapore when it was introduced to the public in 2003. As a persuasive strategy, the prime minister, ministers, and all members of parliament from the ruling party drank a bottle of NEWater during their official duties and public appearances. As a result, the acceptance rate was 98% among survey respondents, with 82% trusting direct use and only 16% relying on indirect use (Guan & Toh, 2012).

In the contemporary period, the 20th century was marked by the development of the legal-administrative basis for the safe use of WW as a source for water and fertilizers. The 21st century, on the other hand, has been highlighted by technological advances and by the different scenarios that require better quality water.

Now, it is necessary to concentrate efforts on awareness-raising actions, in addition to technological development and achieving legal-administrative security. This could be the path to a new era for water reuse in the 21st century. Thus, a transparent approach with user communities is needed, in addition to the implementation of pilot projects to instill confidence between the producer and the user of this new water.

The aforementioned factors led to the application of the practice for more noble uses, and even in the driest regions of the planet. Potable use, direct or indirect, requires advanced treatment technologies, appropriate regulatory framework, complex logistics of water resource management, more assertive decision-making, and a more engaged and participant society.

Some countries in the world already practice indirect potable reuse in an institutionalized way, such as the United States, Australia, Singapore, England, Belgium. Only the United States, Namibia, and South Africa practice direct potable reuse, for reasons of absolute necessity. Their treatment plants started operation between the late 1990s and early 2000s (Santos *et al.*, 2022).

However, the uses that demand less restrictive water qualities, whose risks, and their contours are already widely known by science, have not yet advanced as they should, especially in the poorest regions of the world that suffer from water scarcity. Therefore, the first half of the 21st century may be the stage for this great transformation: it should produce more water for the necessary advances in sustainable socioeconomic development, and especially, to guarantee human dignity, with available water in the quantity and quality required for its various uses.

5. CONCLUSION

We can observe behavior of society in relation to the triad *valuation x devaluation x revaluation* of WW throughout our history. The understanding of the concept 'VxDxR/WW Historical Development' is of great relevance for the guidance of public policies, regional strategic planning, and the production of social instruments of education to achieve the acceptance of such practices.

For most of the history of society's development, the understanding of the benefits of waste for the fertilization of fields prevailed. This understanding must be resumed in the face of current society, in order to contribute to the acceptance of water reuse and to its institutionalization as a safe and responsible practice. Throughout history, the WW *valorization* period is much longer than the *devaluation* period.

The first 3,500 years from antiquity to the Roman period and the first half of the Modern Age were characterized by the *valorization* of WW. However, with the emergence of epidemics and the acceptance of the Microbial Theory, society started to connect WW (and pathogenic microorganisms contained therein) to the proliferation of diseases. At this point, the period of *devaluation* of WW begins, which lasted approximately 150 years, until the beginning of the contemporary period. In the last 100 years, since the beginning of the Contemporary Age, there has been an attempt to revalue the WW, with scientific, legal, and technological advances. These advances may make the first half of the 21st century an important stage for the dissemination of technical-scientific knowledge for the recovery of the *value of WW*.

A true paradigm shift is needed to guide appropriate decision-making that allows and encourages advances. In this sense, water circularity, with its economic, environmental, technological, social, institutional, and political factors, must be taken as the basis of actions to define appropriate public policies, in the context of efficient water management. These policies must follow paths for structuring regulatory frameworks appropriate to different regional characteristics, in order to guarantee a safe, responsible, sustainable and economically viable water reuse practice.

Finally, it is understood that the *valorization* of WW began with observation; *devaluation* as an effect of the Industrial Revolution and the spread of diseases; and *revaluation* as a consequence of droughts and more recently the drive of climate change. In the 21st century, it is necessary to concentrate efforts to achieve public acceptance, in addition to investing in technology and regulatory frameworks.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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