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Progress on legal and practical aspects on water reuse with emphasis on drinking water – an overview

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ABSTRACT

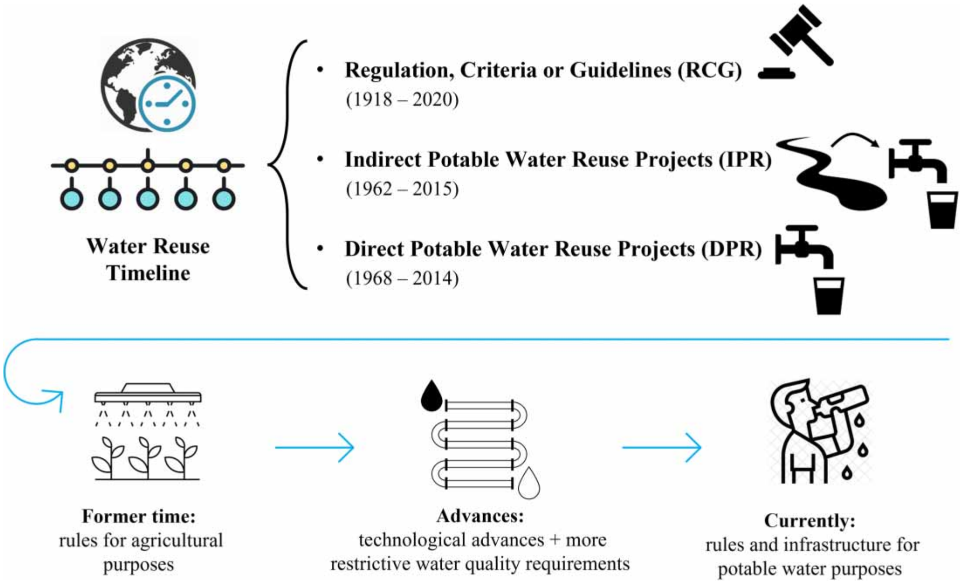
The present study highlights the evolution, progress and prospects of future practices of water reuse in the world. The objective was to produce a comprehensive timeline on the global evolution and progress of water reuse. This was achieved through the analysis of the state of the art on the subject. The present study is a qualitative research, where three aspects have been considered to highlight the global evolution of water reuse: i) Regulations, Standards, Criteria or Guidelines (RSCG); ii) Indirect Potable Reuse Projects (IPR); and iii) Direct Potable Reuse Projects (DPR). The study focused on both legal and practical aspects of water reuse and considered three timelines in the context of RSCG, IPR and DPR: 29 RSCG instruments, institutionalized from 1918 to 2020, where only four instruments were solely dedicated to drinking water reuse; 10 IPR projects; five DPR projects. To achieve good, effective results, the regulatory framework must support the objectives of a structured water reuse policy in addition to guaranteeing legitimacy and maintaining public confidence. Integrated water and wastewater management, based on technological and scientific advances, has become a relevant aspect for implementation of more adequate measures by decision makers to address future global water challenges.

Key words: direct potable reuse, guidelines, indirect potable reuse, regulations, timeline, wastewater

HIGHLIGHTS

- The timeline on Regulation, Criteria or Guidelines spanned from 1918 to 2020.
- The timeline on Indirect Potable Water Reuse Projects ranged from 1962 to 2015.
- The timeline on Direct Potable Water Reuse Projects was from 1968 to 2014.
- The criteria used were initially adopted for agricultural and irrigation uses
- Technological advances facilitated the production of better-quality water reuse.

GRAPHICAL ABSTRACT



INTRODUCTION

Recognition of water and sanitation as a human right by the United Nations (UN) has globally influenced advances in policies that promote improvements in availability, physical accessibility, quality/safety and acceptability of water and sanitation services (UN 2010). However, several challenges still exist and there is great inequality between developed and developing countries (JMP 2019). Global statistics show that 5.3 billion people have access to safe drinking water while 3.4 billion have adequate sanitation. Half of the global population has available facilities to wash their hands with soap (JMP 2019). Remarkably, lack of sanitation generates an average economic loss of 1.3% of world GDP (WHO & UNICEF 2020). Apart from physical scarcity, water quality is a risk factor for drinking water supply and human health.

It is in this perspective and desire to change this global framework that water and sanitation issues appear to be cross-cutting all the United Nations sustainable development goals and is prominent in SDG6–ensuring availability and sustainable management of water and sanitation for all. By setting targets and indicators to be achieved by 2030, SDG6 represents an important driver for the universalization of water and sanitation in the world, by reducing future global risks and similarly strengthening the right to access water and sanitation. Tortajada (2020) reinforces the importance of reuse for potable and non-potable purposes to achieve the goals established for the SDGs.

Water reuse has been practiced since the pre-historic era. Nowadays it is mainly used for irrigation, industrial water supply and indirect potable reuse. Angelakis *et al.* (2018) compiled the evolution for five periods as described:

- In prehistoric times (*ca*. 3200-1000 BC), the first indications of the utilization of wastewater for irrigation and fertilization of agricultural lands extended back ca. 5000 years to the Bronze Age civilizations (e.g. Minoan and Indus Valley).
- In historical times (*ca*. 1000 BC-330 AD), some temples of Ancient Greece (Acropolis and Agora) already had wastewater and rainwater for irrigation and fertilization of orchards and agricultural fields.
- During medieval times (*ca*. 330 AD-1400 AD), Europe was preoccupied with wars and there was little focus on improving water and sanitation services.
- In the modern times (*ca*. 1400 AD-1900 AD), great epidemics in several regions in the world led the authorities to recognize the need for safe drinking water and sanitation. Thus, sewage farms have gained space across the world, with the use of sewage in agricultural fields. At that time, the practice was understood as wastewater treatment and in view of the accelerated population growth, a new interest in more compact sewage treatment technologies emerged.
- In the contemporary times (1900 AD-present), significant technological and scientific innovations along with a marked growth in the implementation of wastewater treatment plants (WWTPs) could handle large volumes of wastewater for

direct discharge to waterways and the ocean. However, water reclamation and reuse has regained popularity due to the challenges of population growth, megacities urbanization and climate change.

Windhoek was the first city in the world to introduce planned potable reuse after it became apparent in the early 1950s that within ten years, serious water problems would arise in the city due to limited natural water resources (Scientiae 1969). The Groundwater Replenishment System in Southern California launched in 2008 is the world's largest advanced water purification system for potable reuse. In Singapore, NEWater has grown from a demonstration-scale project to a sustainable water source able to meet 40% of the country's water needs and is projected to meet up to 50% of future water needs (Kog 2020). In South Africa, a state-of-the-art advanced water treatment plant (WTP) was commissioned to treat the acid mine water that has been accumulating from the mines in Emalahleni, an industrial town surrounded by coal producing mines, steel manufacture and coal-fired power stations. The town's water security had been threatened by low water quality due to high amounts of dissolved metals and salts accumulating in the catchment (Naidu 2012).

Potable water reuse provides a cost-effectiveness option to provide a renewable and resilient drinking water supply. Wastewater reuse is a growing practice in the world, especially in countries or regions experiencing water shortages such as the United States of America (USA), Australia, Israel, Western Europe and Mediterranean Region). Frijins *et al.* 2016 claim that the production of drinking water from reclaimed water has a lower cost when compared to the cost of importing water from neighboring and more distant areas. It is for this reason that some regions have adopted potable reuse since their closest sources are increasingly polluted.

The purpose of this study is to produce a comprehensive timeline on the global evolution and progress of water reuse. Given the difficulty in performing a complete approach to the practice of different modalities of non-potable reuse in the world, the paper focused on the practical aspects with respect to potable uses only. Potable reuse requires advanced technology to produce reclaimed water of acceptable quality. Thus, in order to illustrate the practical advances of water reuse in the world, a timeline on the main potable reuse plants currently operational in the world was presented in addition to the timeline on the regulatory framework.

METHODS

This paper intends to comprehend existing knowledge (without conducting an exhaustive review of the literature), in order to identify points of consensus, controversy and gaps related to the evolution of the practice of water reuse in the world. The experience acquired by different regions of the world were considered, in both legal and practical aspects. Examples and experiences throughout the five continents, (Africa, Australia, Europe, Latin America and the USA) were described.

Water reuse is mainly used for irrigation purposes. There are few facilities and regulations for potable reuse. The paper highlights facilities for drinking water (IPR and DPR) and all the legal aspects for water reuse that are an essential tool for the regional institutionalization of water reuse practice. Potable water reuse has two methods (Figure 1): Indirect Potable Water Reuse and Direct Potable Water Reuse. The study considered three timelines for:

i. **Regulations, Standards, Criteria or Guidelines (RSCG)** is an essential tool for the regional institutionalization of water reuse practice. Regulatory frameworks address legal aspects like mandatory and non-mandatory standards, criteria, or guidelines. *Standard* is a rule or measure established by an authority; *criteria* are the basis for the standards and developed based on available data and scientific opinion; *guidelines* are voluntary, advisory, and non-enforceable rules that are used prior to development of standards or regulations; *regulation* is when the criteria or guidelines are officially adopted as a law.
ii. **Indirect Potable Water Reuse Projects (IPR)** involves the dilution of the treated wastewater in the receiving surface water prior to raw water abstraction for treatment and subsequent drinking water distribution. The paper outlines indirect potable reuse projects currently in operation or designed for this purpose.
iii. **Direct Potable Water Reuse Projects (DPR)** is when the effluent from the advanced treatment is directly sent to the WTP or the drinking water distribution system. The timeline for the direct potable reuse projects currently in operation or designed for this purpose has been constructed.

Figure 1 shows the schematic drawing of both types of potable reuse, (a) DPR and (b) IPR, and their main characteristics.

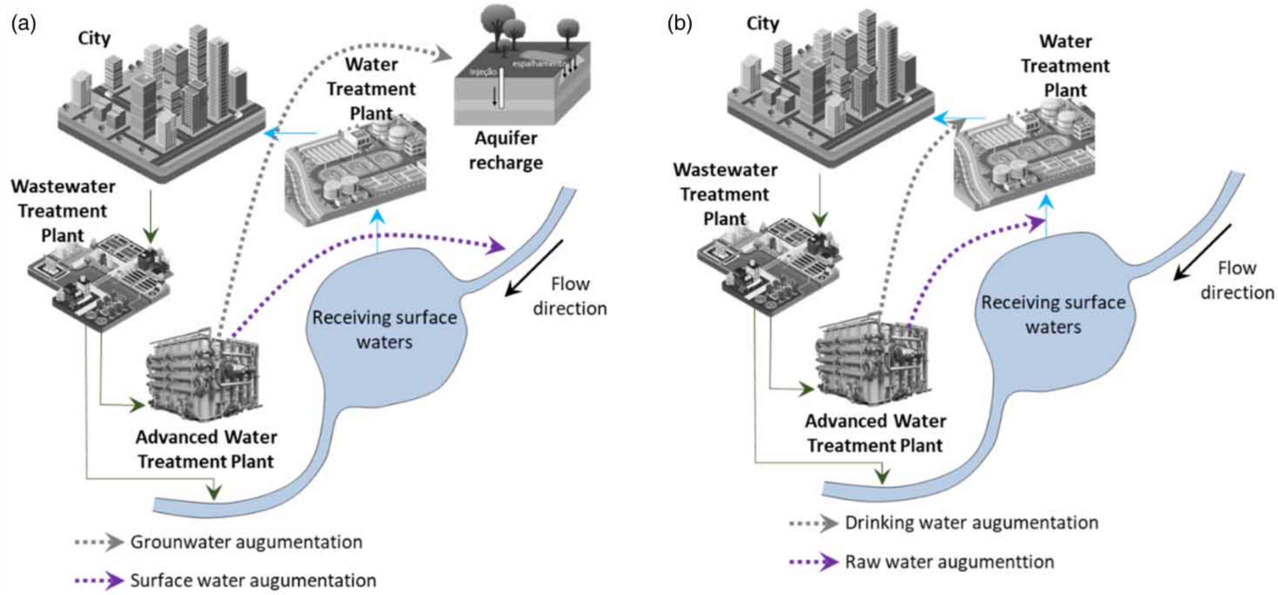


Figure 1 | Schematic view of indirect potable reuse (a) and direct potable reuse (b). *Source:* Adapted from Angelakis *et al.* (2018).

RESULTS AND DISCUSSION

The results have been presented separately for (1) RSCG, (2) IPR and (3) DPR. The timeline for RSCG spans up to 2020 whilst the timelines for facilities stretch up to 2014/2015 only. This is because regulations are continuously updated, and hence only most recent instruments are available. For facilities, planning and construction of projects can take up to ten years before project completion. Whilst it may seem like there are no recent projects in DPR and IPR, on the ground, projects may still be in the implementation process whilst the timeline considers projects currently in operation. Each of the three aspects (RSCG, IPR and DPR) are described extensively after the respective timeline. Future challenges are also discussed at the end of the section. The countries and/or states included in the present study, in terms of legal aspects (RSCG) and the distribution of IPR and DPR projects, are highlighted in Figure 2.

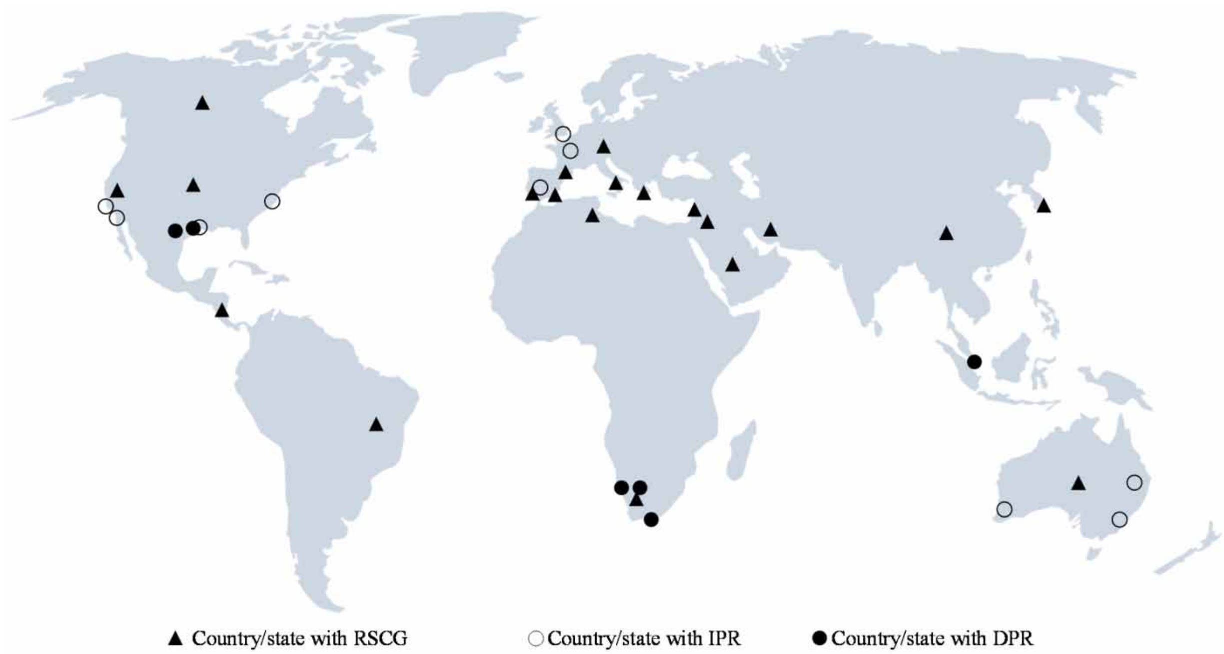


Figure 2 | Location of RSCG, IPR, and DPR coverage in this study.

Regulations, standards, criteria or guidelines

The timeline about RSCG can be observed in Figure 3. The documents discussed here have been updated continuously and cited by many authors. Thus, to facilitate understanding, updates and other specific features can be seen in supplementary materials.

The first regulation in the world was in the State of California, USA, in 1918, although water reuse guidelines for the whole country were only established in 1980 (with updates in 1992, 2004 and 2012), by the United States Environmental Protection Agency (US EPA). These guidelines are non-mandatory and not binding on water reuse utilities (Shoushtarian & Negahban-Azar 2020). Lahnsteiner *et al.* (2018) highlight that the guidelines of Namibia were published in 1998 whilst Australia published guidelines almost one decade later (2006) although Khan & Anderson (2018) claim that Australia was the first country in the world to publish regulations for potable reuse. World Health Organization (WHO) then published in 2017 (Angelakis *et al.* 2018; Shoushtarian & Negahban-Azar 2020) and California, USA in 2018 (Olivieri *et al.* 2020).

Although China implemented initial water reuse criteria in 2002 (Chen *et al.* 2017), specific regulations for water reuse were only published in 2008 (Shoushtarian & Negahban-Azar 2020). Five years later, the overall rate of water reuse in China's urban areas was around 12% (Chen *et al.* 2017). According to Liao at al. (2021), wastewater treatment and reclaimed water are not well developed in most Asian countries and regions. Nevertheless, China is the largest user of reclaimed water globally, with water reuse quantity of 7.1 billion m^3/year in 2017, followed by the USA, which reused 6.63 billion m^3/year of water in 2018 (Liao *et al.* 2021). From 2009 to 2015, the amount of reclaimed water use in China increased rapidly, but still accounted for less than 1% of total water consumption (Zhu & Dou 2018; Qu *et al.* 2019). In Brazil, the water reuse rate of treated wastewater is 1.5%, whilst Portugal has an almost similar value of around 1.2% (Santos & Vieira 2020), and the USA has approximately 1% (Mukherjee & Jensen 2020). However, Lima *et al.* (2021) indicate that all the treated wastewater flow rates in Brazil (with organic matter removal efficiency greater than 80%) represent 9% of the total irrigation water demand in the country. In Israel, with the first water reuse regulation published in 1952 (Jeong *et al.* 2016), 87% of treated wastewater is reused, representing 40% of water demand for irrigation in the country (Marin *et al.* 2017).

Based on a request from Israel, the first International Organization for Standardization (ISO) standards for water reuse in agriculture were issued in 2010; the next ISO standard for water reuse was proposed by Japan and were to be established alongside with Israel and China, in 2015 (Shoushtarian & Negahban-Azar 2020). In 2020, ISO published a series called 'Guidelines for treated wastewater use for irrigation projects, divided into four parts (ISO 2020). It is important to highlight that the series published by ISO in 2020 suggests an approach called 'fit-for-purpose' which involves the production of reclaimed water of adequate quality to the needs of the end users. ISO aims to encourage the development of regulations and documents compatible with the reality of each country (Rebelo *et al.* 2020).

The World Health Organization (WHO) has played a very important role in establishing global regulatory documents which are particularly important for regions with water scarcity and low socio-economic development, such as Latin America, the Caribbean, Asia, and Africa. Many countries have adopted WHO guidelines, modifying them according to their geographical, economic, and epidemiological idiosyncrasies (Jeong *et al.* 2016).

Large territorial countries like Brazil, USA, Australia and Canada inevitably end up setting different standards for each state or county, considering their distinct administrative and institutional organization. Additionally, Brazil, USA and Australia have defined non-mandatory guidelines at national level, to guide the strategic planning of states, counties and municipalities. However, the Canadian context lacks foundational guiding documentation and adequate policy on water resources recovery, considering wastewater as a resource, with community engagement (Nixdorff *et al.* 2021).

In the USA, 28 out of 48 states had adopted specific guidelines for water reuse by 2017 (Shoushtarian & Negahban-Azar 2020) whilst in Brazil, only five out of 26 states had published regulations with water quality standards by 2010 (Santos *et al.* 2020). In 2017, Brazil introduced a national program called *Interáguas* which defined water reuse guidelines, although they have not achieved results as expected (Santos & Vieira 2020; Santos *et al.* 2020).

Globally, it has been observed that water reuse regulations have evolved around three main aspects:

i. Effects of climate change, surface water pollution and increased water consumption due to population growth require strategic planning by the government to incorporate alternative water sources into existing water matrices. This type of planning action only becomes effective through the enactment of regulatory instruments with safe standards, guidelines, and paths for the institutionalization of practice.

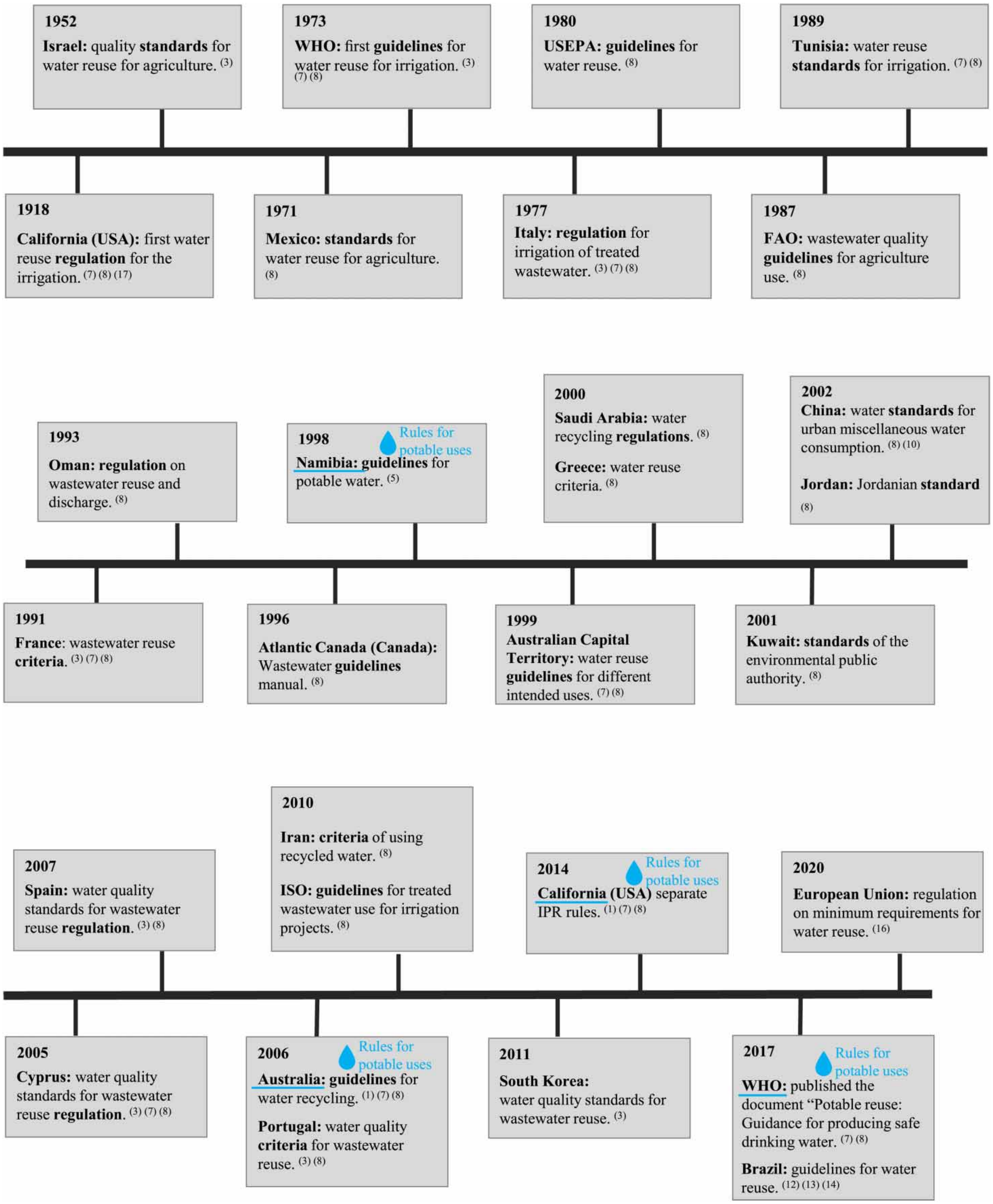


Figure 3 | Timeline of global water reuse development (Regulation, Standard, Criteria or Guidelines – RSCG). *Note*: For documents updating, consult the supplementary material. *Source*: (1) Mukherjee & Jensen (2020). (3) Jeong *et al.* (2016). (5) Lahnsteiner *et al.* (2018). (7) Angelakis *et al.* (2018). (8) Shoushtarian & Negahban-Azar (2020). (10) Chen *et al.* (2017). (12) Brazil (2017). (13) Santos *et al.* (2020). (14) Santos & vieira (2020). (16) EU (2020). (17) Olivieri *et al.* (2020).

ii. Remarkably, it is important to note that the initial actions were taken by regions with water shortages: California (USA), Israel, Namibia, Australia, and the Mediterranean countries. However, different regions have taken different paths, depending on their specific characteristics and factors of socio-economic development. Israel has consolidated itself worldwide with substantial knowledge regarding the reuse of water in agriculture, while Namibia, California and Australia have chosen to move towards adopting standards for potable reuse.

iii. Many regions started their regulatory processes with flexible standards and for less noble specific purposes, due to limited scientific knowledge about the impacts of reuse actions on public health and the environment. To incorporate technological advances and the emergence of new water demands, the regulations have been updated. For example, according to Olivieri *et al.* (2020), in the state of California, even before the enactment of the 1918 reclaimed water regulations it was reported in 1910 that there were 35 California communities using sewage for farm irrigation, 11 without any treatment and 24 after septic tank treatment (Ongerth & Jopling 1977). Over the years, the state regulation started to incorporate scientific and technological advances, setting more restrictive criteria and new crops for irrigation (1968), more restrictive criteria for landscape irrigation in unrestricted areas, and even for aquifer recharge (1978), eventually adding criteria for indirect potable reuse with aquifer recharge (2014) and surface water augmentation (2018) (Olivieri *et al.* 2020).

Indirect potable water reuse projects

The timeline of Indirect Potable Water Reuse Projects is shown in Figure 4.

Initially, water reuse practice in the world progressed with advances in technology, regulation, and increase in water and sanitation services demand.

Recently, the availability of alternative sources of drinking water supply such as reuse and desalination has increased considerably since traditional sources of water (surface and underground) have become increasingly polluted (Mukherjee & Jensen 2020). However, at a global scale, indiscriminate and unplanned schemes of indirect potable reuse are practiced, known as *de facto* potable reuse. According to Angelakis *et al.* (2018) '*de facto* potable reuse', also referred to as unplanned drinking reuse, is defined when a source for drinking water follows a wastewater discharge upstream. Wastewater discharges represent a significant part of the flow of receiving water bodies. Dalezios *et al.* (2018) claim that in some drinking WTPs, especially under low-flow conditions, a significant proportion (up to 75%) originated as wastewater effluent from upstream communities.

Table 1 shows a summary of the IPR projects characteristics referred to in this study.

- The **Montebello Forebay Groundwater Recharge Project (MFGRP)** was a result of several planning strategies against water scarcity in Southern California. According to Sanchez-Flores *et al.* (2016), the project started in the late 1950s and was built in 1962, making it the first planned IPR project in California and one of the pioneers in the USA. In this

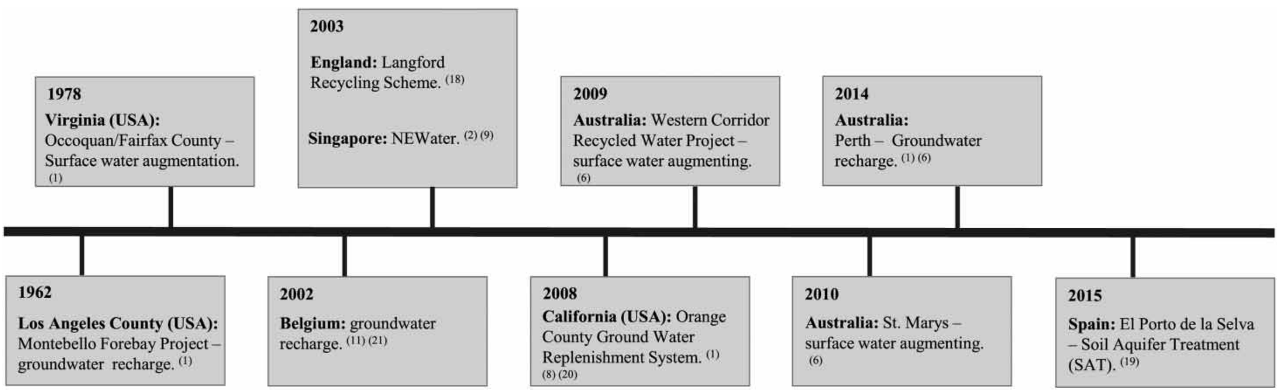
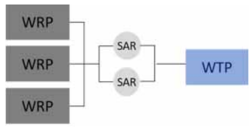
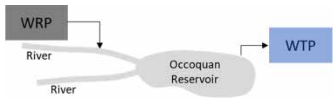
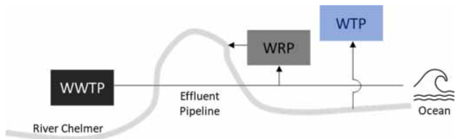
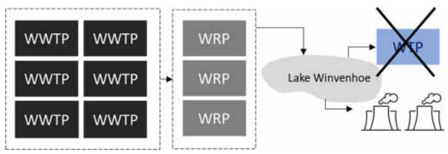
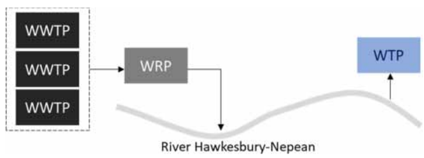
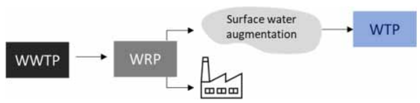


Figure 4 | Timeline global water reuse development (Indirect Potable Water Reuse Projects – IPR). *Source*: (1) Mukherjee & Jensen (2020). (2) Hartley *et al.* (2019). (6) Khan & Anderson (2018). (8) Shoushtarian & Negahban-Azar (2020). (9) Lefebvre (2018). (11) Scholes *et al.* (2021). (18) Lawton *et al.* (2021). (19) Fajnorová *et al.* (2021). (20) Reny *et al.* (2021).

Table 1 | Details and characteristics of IPR

Project	Country	IPR	Capacity (10^6 m^3/yr)	Schematic diagram
MFGRP	United States	AR	62 (1)	
OFFV	United States	SA	75 (1)	
OCGRS	United States	AR	138 (2)	
LSR	United Kingdom	SA	15 (1)	
TWRS	Belgium	AR	3 (2)	
PGRS	Australia	AR	28 (3)	
WCWRP	Australia	SA	80 (3)	
SMAWRP	Australia	SA	18 (3)	
NEWater	Singapore	–	82 (4)	
EPSGR	Spain	AR	0.04–0.05 (19)	

Note: AR, aquifer replenishment; SA, surface augmentation; WRP, water recycling plant; SAR, spreading aquifer recharge; IAR, injection aquifer recharge; WWTP, wastewater treatment plant; WTP=water treatment plant. *Source*: (1) Sanchez-Flores *et al.* (2016); (2) Tortajada (2020); (3) Khan & Anderson (2018); (4) Lefebvre (2018). (19) Fajnorová *et al.* (2021).

project, water coming from three Water Recycling Plants (Whittier Narrows WRP, San Jose Creek WRP and Pomona WRP) is distributed over two spreading basins, known as 'Rio Hondo Spreading Ground' and 'San Gabriel Spreading Ground' to recharge the aquifer. The spreading is responsible for 35% of the total groundwater basin recharge (EPA 2012; Sanchez-Flores *et al.* 2016).

- The **Occoquan/FairFax Virginia (OFFV)**, implemented in 1978, was the first project of surface water augmentation from treated wastewater in the USA and is considered the most relevant in terms of regional collaboration. In this case, treated wastewater with a high degree of purification, collected from the metropolitan area of Washington D.C., is discharged into the Occoquan Reservoir, upstream from the Fairfax WTP in Virginia (EPA 2012; Sanchez-Flores *et al.* 2016). Furthermore,

the Occoquan Reservoir protects the water quality of the Chesapeake Bay because it acts as a trap for sediments and pollutants (Suazo 2021). Water reuse represents approximately 10% of the water that enters the Occoquan Reservoir in a common year, and the ratio reaches 80% during drier years (NRC 2012).
- The **Orange County Groundwater Replenish System (OCGRS)** is the largest water reuse facility of IPR in the world. It started aquifer recharge operation in 1976 and is in operation since 2008 applying the most advanced treatment technologies (Reny *et al.* 2021). The complete project has a complex reuse scheme which involves the advanced water purification facility in Fountain Valley and produces 378.5 million liters per day of highly treated potable-quality water from secondary treated wastewater effluent provided by the Orange County Sanitation District (Reny *et al.* 2021). Purified water from an advanced treatment process is infiltrated into the aquifer through injection wells, spreading ponds, and pipeline transmission system, in north/central Orange County (Reny *et al.* 2021), where the mixture serves as a source of water supply for more than 850,000 people (Tortajada 2020) in Orange County, California, USA. According to Reny *et al.* (2021), the recharge facilities together with the advanced water purification facility are known as Orange County Groundwater Replenishment System (OCGWRS).

In Europe, the United Kingdom, Belgium and Spain have been operating IPR systems since 2002, 2003 and 2015 respectively:

- In the United Kingdom, the **Langford Scheme Recycling (LSR)** has been operating since 2003 and was the first IPR in Europe (EPA 2012; Sanchez-Flores *et al.* 2016). The project started with studies conducted between 1993 and 1999, driven by the drought events of the 1990s in the southeast of the country. In order to protect the drinking water source in the Chelmer River, the Chelmsford WWTP effluent upstream is conveyed for 15 km and discharged directly to the sea. However, part of the effluent is derived for advanced treatment in the LSR and later discharged into the Chelmer River for increased flow and incorporation into the water abstracted by Langford WTP about 3 km downstream (Sanchez-Flores *et al.* 2016). According to Tortajada (2020), the LSR operates only when the flow of the Chelmer River is low, supplying up to 70% of the flow during dry periods. EPA (2012) claims that the largest flow of reuse produced by LSR occurred in the droughts of 2005–2006 and 2010–2012. According to Lawton *et al.* (2021), planned water reuse is not widely practiced in the UK.
- According to Frijins *et al.* (2016), the **Torreele Water Reuse Scheme (TWRS)**, located in the Belgium south-west coast in operation since 2002, produces high-quality water from the WWTP Wulpen effluent for artificial aquifer recharge. The abstracted groundwater is used for drinking water supply. In this case, 40% (approximately 60,000 inhabitants) of the community's water consumption is derived from the reuse (Tortajada 2020). Also, installation of a subsurface wetland system for treating reverse osmosis concentrate from the Torreele Water Reuse Plan has been operating in pilot scale since 2011. The aim is to reduce permit fees associated with the discharge of nutrients and metals to the North Sea (Scholes *et al.* 2021).
- El Porto de la Selva is a small tourist town with less than a thousand inhabitants in Spain. Nevertheless, during the summer months, the population increases by a factor of four, leading to rapid decline in groundwater levels of local aquifers with limited capacity (Fajnorová *et al.* 2021). Current tertiary treatment and a non-potable reuse infrastructure was designed for street sweeping, non-agricultural irrigation, and infiltration via the dry riverbed to prevent saltwater intrusion in summer months (Frigola *et al.* 2015). Since 2015, **El Porto de la Selva Groundwater Recharge (EPSGR)**, during winter months, has been testing regarding its potential to strengthen the local water reuse strategy. It was projected to infiltrate 200 m^3/d of tertiary treated effluent during 200–240 d/yr (outside of the tourism season, i.e. the period from October to May), resulting in 40,000–48,000 m^3/yr additional supply recharged to the groundwater (about 10% of the abstracted groundwater) (Frigola *et al.* 2015; Fajnorová *et al.* 2021). According to Fajnorová *et al.* (2021), the conventional wastewater treatment in El Port de la Selva consists of biological nutrient removal with phosphorus precipitation and secondary clarification. The secondary effluent is further treated in a tertiary treatment plant equipped with dual media filtration and UV disinfection.

In Australia three IPR projects deserve to be highlighted:

- The most important potable water reuse project in Australia is the **Perth Groundwater Replenishment Scheme (PGRS)**. Its operation started in pilot scale in 2006 and it reached full scale in 2014. Water quality monitoring guarantees minimum risks to public health (Khan & Anderson 2018; Mukherjee & Jensen 2020). According to Khan & Anderson (2018), the effluent of Beenyup WWTP, purified by ultrafiltration, reverse osmosis and UV-disinfection, is discharged into the aquifers Yarragadee and Leederville to serve up to 100,000 inhabitants.

- The **Western Corridor Water Recycling Project (WCWRP)**, built in South-East Queensland, was designed in 2007 for IPR, considering water surface augmentation, from the combination of the effluents of six WWTP (Bundamba, Goodna, Oxley, Wacol, Luggage Point and Gibson Island) for advanced treatment in three other plants (Bundamba, Luggage Point and Gibson Island) and later discharged into the Lake Winvenhoe. However, since 2009 it has operated below the nominal capacity and has been used to supply highly treated recycled water to two power stations in the region (Tarong and Swanbank Power Stations) as cooling water (Khan & Anderson 2018).
- The **St. Marys Advanced Water Recycling Plant (SMAWRP)** aims to complement the flow of the Hawkesbury-Nepean River, about 17 km upstream of the catchment for supply in Richmond. The SMAWRP operates with treated effluents of three WWTPs (Penrith, St Marys, and Quakers Hill), located in western Sydney, which are subjected to ultrafiltration and reverse osmosis before being released into the river (Khan & Anderson 2018).

Indirect potable water reuse has been implemented in Singapore over the last 15 years. Until 2018, the reclaimed water, called **NEWater**, provided an average of 30% of the nation's water demand (Lefebvre 2018); currently, it means 40% and, in the future, 50% (Kog 2020). The original plan called for a greater percentage, but industrial demand for high quality recycled water increased, reducing demand for potable water. This implies that in Singapore, high quality water from advanced wastewater treatment facilities is mainly used in industrial application. The current NEWater production process is a combination of conventional activated sludge, microfiltration or ultrafiltration, reverse osmosis and ultraviolet disinfection (Li *et al.* 2020). According to Sun *et al.* (2021), how to improve the environmental sustainability of the NEWater production process towards less sludge generation, reduced energy consumption and small footprint has become an emerging challenge towards future water sustainability.

Direct potable water reuse projects

The timeline of Direct Potable Water Reuse Projects is shown in Figure 5.

Namibia and South Africa operate the main potable reuse plants in the African continent. However, the project operated in Namibia is outstanding for producing safe drinking water for more than 50 years. Hartley *et al.* (2019) cite surveys carried out in 2010 and 2016 by different institutions which demonstrate acceptance and confidence from consumers.

In the early 1960s, Windhoek, the capital city of Namibia, with almost 400,000 inhabitants, started operating a wastewater treatment plant (Gammams WWTP) capable of producing scientific assessed high-quality effluent for drinking water purposes. During a severe water crisis in 1968, the project was put on full scale for direct potable reuse. In the 1990s, another severe drought led to the design of a new water reuse facility, which started operating in 2002, increasing the previous capacity by 4.5 times (Rensburg 2016). It is called the **New Gorengab Water Reclamation Plant (NGWRP)**, and provides for approximately a quarter of Windhoek's potable water demand (Wallmann *et al.* 2021). Currently, NGWRP provides water for domestic use (Lahnsteiner *et al.* 2018), whilst Gammams WWTP still produces reclaimed water for irrigation of public parks

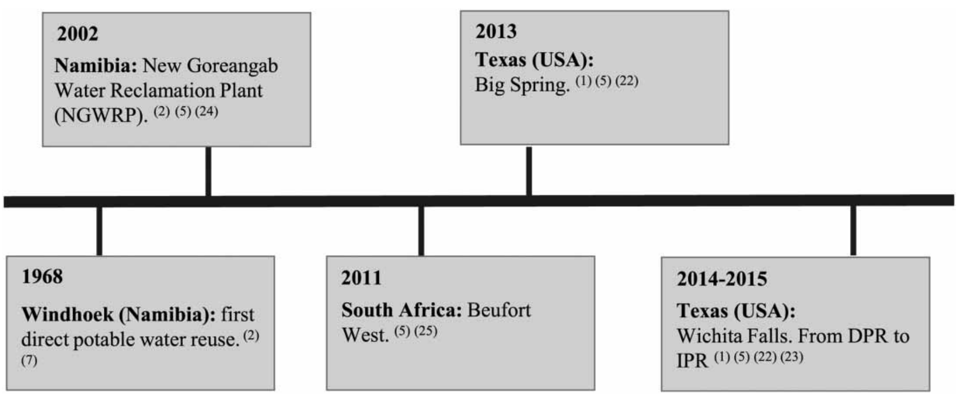


Figure 5 | Timeline of global water reuse development (Direct Potable Water Reuse Projects – DPR). *Source*: (1) Mukherjee & Jensen (2020); (2) Hartley *et al.* (2019); (4) Sanchez-Flores *et al.* (2016); (5) Lahnsteiner *et al.* (2018); (7) Angelakis *et al.* (2018); (9) Lefebvre (2018); (22) Wester & Broad (2020); (23) Nix *et al.* (2021); (24) Wallmann *et al.* (2021); (25) Visser (2021).

and sports fields in the city (Rensburg 2016). According to (Lahnsteiner *et al.* 2018) the water produced in the NGWRP is mixed directly into the drinking water supply pipe.

Beaufort West Water Reclamation Plant (BWWRP) is operated in South Africa from secondary effluent treatment. The quality of water produced at BWWRP exceeds the national drinking water quality standards. In this way, the water is mixed directly with water treated in the conventional WTP (Lahnsteiner *et al.* 2018). According to Visser (2021), in January 2011, Beaufort West, a rural area in South Africa, started the implementation of South Africa's first reclamation plant and the project was completed within six months. In this case, treated wastewater effluent is conveyed directly to a water treatment facility for further treatment to attain drinking water standards. This further treatment includes processes such as phosphate removal, pre-disinfection, ultra-filtration, reverse osmosis and advanced oxidation. The plant produces 10,800 L/d of drinking water. The reclaimed water is pumped into a reservoir and blended with water from the Gamka Dam, and 36 boreholes in six aquifers at a ratio of 1:4 (Visser 2021).

In the USA, the only DPR project currently in operation is in the state of Texas, a region known for its low rainfall and arid climate. The region's low water availability has driven the need to implement and operate DPR schemes. According to Wester & Broad (2020), Wichita Falls and Big Spring implemented and operated the first DPR projects in the USA. However, currently, only Big Spring is in operation as DPR and Wichita falls operates as IPR. Mukherjee & Jensen (2020) claim that the DPR pilot project in US, was in Denver, Colorado where a demonstration plant was operated for research and development purposes from 1980 to 1993.

In the city of Wichita Falls the first DPR scheme was considered during a drought in 1990s, although another solution was used until the end of the drought in 2001. Later on, the quality conditions of Lake Kemp (drinking water supply source) required the construction of a microfiltration and reverse osmosis plant in order to treat the increasingly brackish water. The existence of these advanced water treatment facilities was then considered important in decisions to pursue DPR anew. In the latest drought, as levels dropped in Lake Kemp, water quality diminished to the point of being unusable (Wester & Broad 2020).

According to Wester & Broad (2020) and Nix *et al.* (2021), construction of a project to allow the eventual use of DPR scheme (**Wichita Falls Water Reclamation Plant – WFWRP**), began in 2013 and was approved in July 2014 on a temporary basis for six months. The facility produced approximately 5 million gallons of water a day (MGD), creating a 50–50 blend of treated wastewater and water from surface reservoirs. In July 2015, the DPR plant was decommissioned, after rains replenished reservoirs levels (Lahnsteiner *et al.* 2018). Occasionally, the secondary effluent from WWTP was sent to the advanced brackish lake WTP, as a Water Reclamation unit. After treatment, the effluent was mixed with raw water abstracted from the brackish water lake (1:1 ratio) for treatment in the conventional WTP using pre-oxidation, coagulation/flocculation, sedimentation, re-stabilization with CO_2, granular filtration, and chlorination. (Lahnsteiner *et al.* 2018). After the spring rains of 2015, which were considered sufficient to supply the raw water reservoir, the project was transformed into an IPR (Sanchez-Flores *et al.* 2016; Lahnsteiner *et al.* 2018; Wester & Broad 2020; Nix *et al.* 2021). In addition to transition from DPR to IPR, the city of Wichita Falls implemented a new drought management plan with several strategies, presented as a larger portfolio of solutions rather than as alternatives (Wester & Broad 2020).

The **Big Spring Water Reclamation Plant – BSWRP** started operating in April 2013, producing approximately 2 MGD, which was blended with water from traditional sources at a ratio of 20% reused water to 80% raw water before being distributed to several plants in the immediate region for further conventional treatment prior to public consumption. This project, while relatively small in terms of output and percentage, compared with the proposal that would come later in the state, represented the first successfully implemented DPR system in the USA (Wester & Broad 2020).

Currently, **BSWRP** is operated from the dechlorinated tertiary effluent of the Big Spring WWTP, mixed with the raw water from the E.V. Spencer reservoir for treatment in conventional WTP and distribution (Lahnsteiner *et al.* 2018). The reclaimed water is applied directly to the reservoir's raw water pipeline. According to Sanchez-Flores *et al.* (2016) the success of the project was mainly attributed to the transparency of the contracted company, the awareness campaign with regulatory agencies and the inevitable reality of water scarcity in the region.

According to Mukherjee & Jensen (2020), WFWRP and BSWRP have been widely accepted by local communities, although Wester & Broad (2020) claim the near abscence of discussion of the issue during Big Spring city council meetings. However, there have been cases of vociferous opposition towards projects in San Diego, East Valley (Los Angeles) and Tampa city (Florida) which involved similar technologies, mainly because of management and communication approaches. As of 2017, there were few DPR plants in study, planned, in demonstration scale or approved but not yet constructed in US.

Table 2 shows a summary of DPR projects characteristics referred to in this study.

In terms of technology, the process to produce DPR water is long and involves a combination of stages that include (i) physicochemical: coagulation-flocculation; (ii) conventional filtration: sand and carbon filtration (biological and activated granular); (iii) membrane advanced filtration: micro filtration, ultrafiltration, and reverse osmosis; (iv) advanced oxidation process: UV-peroxide and ozonization; (v) disinfection: chlorination, UV and lagoon. Wallmann *et al.* (2021) claim that the technologies used in combination, called multi-barrier systems, can remove specific contaminants for drinking water safety, such as coliform bacteria, antibiotic-resistant bacteria, and antibiotic resistance genes.

Future challenges

Despite the great advances in regulation and application of water reuse in the world, there are many challenges that still need to be addressed:

(a) **Integrated water and wastewater management:** When planning, it is important to consider water and wastewater in an integrated approach unlike the current situation where water resources management issues are still regarded separately from sanitation issues. The concept 'One water', which characterizes the merger between the two units, leads to more thoughtful, rational, and economical solutions that can be implemented to meet future water needs (Angelakis *et al.* 2018).

(b) **Proper regulation:** Although there are many regulatory documents published in different parts of the world, Angelakis *et al.* (2018) point out that there is little standardization globally. It is therefore important to align them to protect public health, the environment, and the global future economy. It is also important to develop comprehensive and flexible solutions, in addition to a regulatory framework together with an efficient water reuse policy based on more realistic risk assessments (Rebelo *et al.* 2020) so that the approach can be applied safely, responsibly, and systemically.

(c) **Planning and investments in low- and middle-income countries:** The regions with low socio-economic development usually get international support (both legal and technical) that often does not match their local realities and needs. Santos & Vieira (2020) emphasize that it is important for the regulatory framework to align with respective local experiences and planning should be the driver of reuse activities in the regions most affected by drought.

(d) **Minimization of rejection (Factor *Yuck*):** As highlighted by Mukherjee & Jensen (2020) the psychological barrier of rejection, known as 'Yuck Factor' is one of the main challenges associated with the difficulty in implementing the practice of water reuse, especially for drinking water projects. Thus, a transparent approach with the receiving communities is necessary, in addition to the implementation of pilot projects to instill trust between the producer and the user of the water reuse (Hartley *et al.* 2019; Mukherjee & Jensen 2020).

Table 2 | Details and characteristics of DPR

Project	Type	Capacity (10^6 m^3/year)	Water reclamation process
NGWRP Namibia	Blended (25/75) directly with drinking water, without additional treatment	8	Pre-ozonization, coagulation, dissolved air flotation, rapid sand filtration, ozonation, biological activated carbon filtration, granular activated carbons filtration, ultrafiltration membrane, disinfection by chlorination and stabilization
BWWRP South Africa	Blended (20/80) directly with the drinking water, without additional treatment	0,7	Pre-chlorination, sedimentation, intermediate chlorination, rapid sand filtration, ultrafiltration membrane, reverse osmosis, advanced oxidation process (H_2O_2/UV) and final chlorination
WFWRP* Texas, USA	Blended (50/50) with untreated lake water, with additional conventional water treatment	7	Pre-chlorination, coagulation, sedimentation, microfiltration, reverse osmosis, UV disinfection; lagoon
BSWRP Texas, USA	Blended (15/85) with untreated lake and reservoir water, with additional conventional water treatment	3	Microfiltration, reverse osmosis, advanced oxidation process (H_2O_2/UV)

Source: Adapted from Lahnsteiner *et al.* (2018); Wester & Broad (2020); Visser (2021); Wallmann *et al.* (2021). *Note*: * when it was operated as DPR.

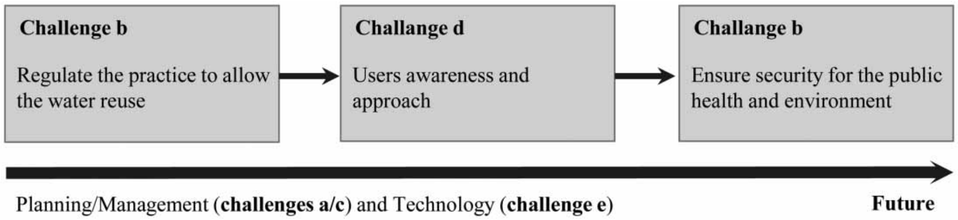


Figure 6 | Integration between challenges and actions needed to boost the systematic practice of water reuse.

(e) **Adaptation of different wastewater treatment technologies for different uses:** As presented by Angelakis *et al.* (2018), technological advances for wastewater treatment have been more striking in the contemporary period, especially in the last three decades. These advances have even allowed the adoption of the practice of potable reuse. However, Tsagarakis *et al.* (2013) emphasize that adequate attention must be given to the quality of water reuse produced by different wastewater treatment technologies, considering that effluents from primary wastewater treatment technologies can be applied in forested lands and parks in a controlled manner. The best quality of water reuse is not only obtained from advanced technologies and high costs, but simple low-cost technologies can also be adopted for non-potable uses where the microbiological risk is lower.

Figure 6 shows the integration between the presented challenges and the actions needed to allow and boost the systematic practice of water reuse

CONCLUSION

The evolution in the last century of the legal and practical aspects of water reuse in the world was outlined. The criteria used in regulation were initially adopted for non-potable applications such as agricultural and irrigation uses. Over the years, technological advances have facilitated the production of better-quality reclaimed water to meet rising drinking water demands due to population growth, and climate change. Thus, the regions most affected by water shortages started their indirect and direct potable reuse projects, according to their specificities and idiosyncrasies.

Currently, it is possible to affirm that water reuse can be a safe practice if the correct paths are adopted to guarantee the safety of public health and the protection of the environment. Many issues still need to be addressed, especially in regions with low socioeconomic development, with challenges in planning, investments, and regulations. Developing countries need to learn from the paths taken by the developed regions to establish more flexible standards, which consider local circumstances whilst adjusting to the development of new technologies and new demands. The initial step is very crucial. To achieve good, effective results, the regulatory framework must support the objectives of a structured water reuse policy in addition to guaranteeing legitimacy and maintaining public confidence. Integrated water and wastewater management, based on technological and scientific advances, became a relevant aspect for implementation of more adequate measures by decision makers to address future global water challenges.

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DATA AVAILABILITY STATEMENT

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

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