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PERSPECTIVE

Sustainable water reuse for water security

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1. Introduction

Water security (or the reliable, resilient availability of and access to water in the quantity and quality needed for all uses) is one of the most critical global challenges faced at present due to its profound impacts on socio-economic development, human health, and the environment. At present, already unsustainable access to clean water is exacerbated by climate change-induced hydrological events such as changing precipitation patterns, drought and flood events and storm intensity, which are altering water resources worldwide both in terms of quantity and quality [1].

Key to sustained global water security is water augmentation through non-conventional sources, including reused or 'recycled' water. This has triggered a paradigm shift from a linear model of water use to a circular one in which wastewater and stormwater are considered resources instead of sources of pollution [2].

In the face of climate-aggravated droughts in water-scarce regions, water reuse has proven to enhance water security for potable and non-potable uses as well as onsite reuse to reduce reliance on freshwater. Objectives include urban water supply (e.g. Windhoek, Namibia; Cape Town, South Africa; Orange County, US; Thessaloniki, Greece; Singapore; Perth, Australia), agricultural irrigation (e.g. Valencia and Murcia regions, Spain; California, US) industrial applications (e.g. Taiwan, Singapore; and Virginia and Florida, US) and the environment (e.g. Orange Country, US; Veurne, Belgium), among others.

Essential to implementing water reuse are governance frameworks (policies, laws and, regulations) that regulate its treatment, quality, and distribution protecting human and environmental health. These frameworks drive strategic planning and ensure resilient, sustained investments in critical areas, including health risk assessments, risk monitoring and management, reporting, information provision, infrastructure development, and public education.

2. Governance frameworks

An estimated 380 billion m^3 of wastewater is produced globally each year, a figure projected to increase 24% by 2030 and 51% by 2050 [3]. Approximately 80% of wastewater produced is not properly treated before disposal, a serious concern for human and environmental health.

At present, reused water is part of the local water supply for 30 million people globally. Despite its enormous potential, it faces recognized impediments such as health concerns, high initial investments, meeting continuously improving governance, and management of public perception. Identifying and managing known or suspected risks is crucial to support appropriate policies that rely on wastewater management being both effective and perceived as being safe.

Against this background, non-potable reuse of treated wastewater is generally acceptable if treated suitably for its intended purpose. Potable reuse on the other hand can be controversial. It can take the form of indirect reuse (IPR) where it requires an environmental buffer before it is accessed for drinking water; or direct reuse (DPR) directly augmenting drinking water supply. Both IPR and DPR have been implemented in at least 35 cities globally [4, 5], and governance and financial frameworks have been developed in all cases.

Internationally, governance frameworks encouraging DPR and IPR include examples such as WHO´s 1973, 1984, 1987, 1989 and 2006 guidelines, and 2017 guidance, the US Environmental Protection Agency's National Water Reuse Action Plan, the EU

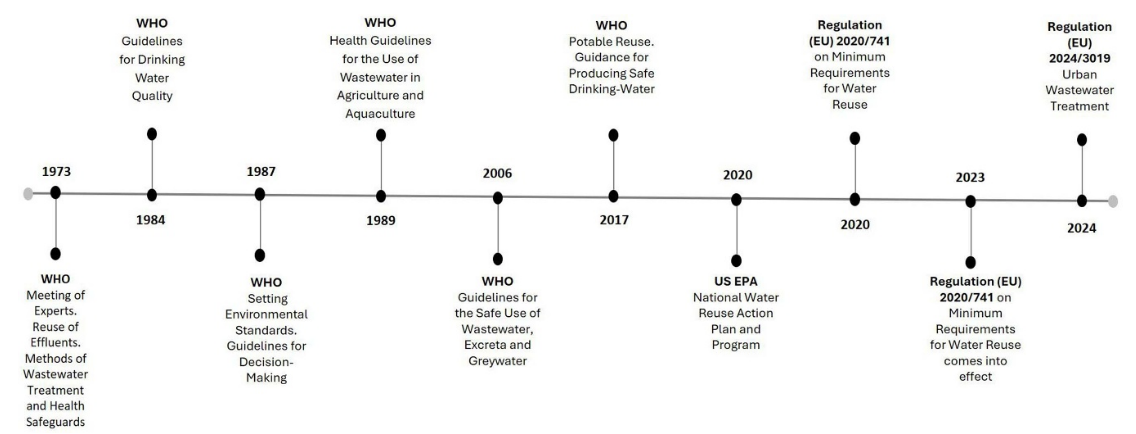

Figure 1. Global regulatory initiatives related to water reuse [6, 7].

Water Reuse Directive 2020/741 and the EU Urban Wastewater Treatment Directive 2024/319 (figure 1). There is no specific EU Directive for potable water reuse, direct or indirect, but none prohibits it. This is currently left for individual countries to self-regulate.

In this Perspective, we discuss three cases where water reuse has been thoroughly implemented to address water security concerns at city (Windhoek), state (California), and country (Spain) levels, and the specific governance arrangements that regulate the practice. Despite the disparity of their geographical scale, the rationale in selecting these cases is due to the governance dimensions and the degree of implementation and integration into policy. In Namibia, water reuse is practiced only in Windhoek with governance frameworks for DPR. In the US, the most advanced state is California with more robust governance in recent years for both IPR and DPR. In Spain, water reuse governance is advanced at the national level. However, IPR is implemented only in specific places and DPR is prohibited.

As a fourth case study, we discuss energy generation and resource recovery in Australia, complimentary to water reuse practices. Australia's National Water Quality Management Strategy encompasses 21 guidelines agreed by all national, state and territory governments and governed through state/territory acts and regulations since, constitutionally, water is a state jurisdictional matter. Water reuse is integrated into guidelines for the management of health and environmental risks, augmentation of drinking water supplies, use for groundwater recharge, and stormwater harvesting and reuse [8].

Wherever adopted, reused water plays a central role to address socio-economic aspects by providing clean water; environmental issues by augmenting river flows, lakes, and reservoirs, wetland management, and recharging groundwater resources improving their water quality, as well as ameliorating saline intrusion; and enhancing circularity by linking water reuse, resource recovery, and energy generation.

Windhoek, Namibia. Namibia is the most arid country in Sub-Saharan Africa. To address water security, DPR has been practiced in Windhoek since 1968, and has played a crucial role in maintaining reliable tap water access. During the 2015–2017 drought, reused water accounted for approximately 30% of the city's total water supply at the peak of the crisis in 2016 [9]. Namibia does not have a stringent regulatory framework or authority and, in Windhoek, despite its long experience, policy and regulatory environments are not particularly strong. This might explain why, aside from Windhoek—where capacity and expertise for reuse have been developed over many decades—little reuse is found elsewhere in the country.

For non-potable reuse, a technical guideline was issued in the early 2000s by Namibia's Department of Water Affairs, Ministry of Agriculture, Water, and Forestry. It established appropriate standards for agricultural water reuse, providing a basis for the Ministry to issue permits. This approach is reflected in the current Water Resource Management Act (Act 11 of 2013), which primarily provides for non-potable reuse in industrial, mining, agricultural, aquaculture and landscaping contexts. The regulations under this Act do acknowledge water reuse for potable purposes but lack any specific policy or further guidance.

During the planning and design phases of the current DPR facility (built in the late 1990s) and a second DPR plant currently under consideration, standards received considerable attention. It was recognized that existing national and regional drinking water standards did not account for the origin of the raw water and so did not include all necessary parameters. Given the global consensus that no raw water source is entirely 'pure' due to prior usage, Windhoek acknowledges that the design parameters and criteria for DPR facilities must exceed the regulatory standards that define the legal minimum for drinking water quality.

California, US. To address water availability concerns, water reuse has been an integral component of water resource planning and management in California for over five decades. The states of Colorado, Texas, Georgia, Florida and Virginia have followed.

Regarding governance, the Policy for Water Quality Control for Recycled Water[5], first adopted in 2009, was amended in 2013 to include monitoring requirements for contaminants of emerging concern. In 2018, it was amended again to incorporate quantitative goals for water reuse, including in coastal areas and those where groundwater has been over-extracted, with annual reporting requirements for wastewater treated and discharged, and reused water produced and used [10].

Between 2019 and 2022, California produced 3.5 billion m^3 of reused water with the potential to cover annual water needs (indoor and outdoor) of 3–6 million households [11]. Per the California Water Supply Strategy, almost 1 billion m^3 of water/year will be reused by 2030, increasing to 2.2 billion m^3 by 2040, by redirecting treated wastewater presently discharged into the ocean [12]. This will contribute to water security in the state which, over the last decades, has come under severe threat due to adverse climate-related events. An example is the Groundwater Replenishment System in Orange County that has averted water shortages during droughts [13].

In 2010, the California State Water Resources Control Board proposed new regulations to augment the supply of public drinking water distribution systems from municipal wastewater. DPR regulations (SBDDW-23-001) were adopted in December 2023 and became effective from 1 October 2024. California is the second state after Colorado to adopt DPR regulations[6]. Such has been the pressure for water recycling that the US Department of Interior [14] announced in November 2024, a sum of $125 m in addition to an earlier announced $179 m for water recycling projects, mostly to enhance Western communities' resilience to drought and climate change.

Spain. Spain has the highest water reuse potential in the European Union [15]. In 2022, 8% of reused water was utilized in the most water-stressed areas, such as Valencia (35%) and Murcia (29%) regions, as well as Canary Islands (29%) mainly for irrigated agriculture [16]. Direct human consumption is not allowed, except during a declared emergency, when the health authorities would be responsible for setting water quality parameters and allowed uses. How such services would be provided during an emergency has yet to be determined.

Reused water was first considered as an alternative source of water in the 1990s. However, it was until 2021 that its implementation was supported through the National Plan for Water Treatment, Sanitation, Efficiency, Savings, and Reuse [17] and the Circular Economy Strategy. The National Plan argues that reused water is less expensive and has less environmental impacts than desalination and water transfers. It is also unlikely to trigger disputes between users in the different basins, as is often the case with water transfers.

Water Reuse Regulations have been approved by the Royal Decree 1085/2024, of 22 October. They address water scarcity and pressure on water resources, promote circular economy, provide an adaptation framework to climate change, and contribute to sustainable water demand. Objectives include ensuring that reused water is safe for the defined uses with a high level of protection of the environment, and human and animal health. They also supplement Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020, on minimum requirements for the reuse of water, applying the provisions on risk management in agricultural irrigation to all other uses of reused water.

Table 1 presents governance frameworks for water reuse in Windhoek, California and Spain. In all cases, laws, regulations and policies have been progressively improved to ensure safety of reused water.

3. Energy production and nutrient recovery

Water utilities are recognizing opportunities for resilient investment in energy production and nutrient recovery. Treatment technologies aimed at meeting new effluent quality standards generally consume more energy. However, wastewater treatment plants (WWTP) *generating* electricity from biogas are being increasingly adopted. They can further generate electricity from solar-voltaic cells mounted on their land or storage pond areas. These energy recovery and efficiency projects, contributing to on-site electricity use or local or national electricity grids considerably reduce the plants' carbon footprints, are helping to balance operational expenses and improve return on investment.

[5] In the rest of the article, we call such water 'reused' rather than 'recycled' for consistency.

[6] In California, 'DPR' refers to the direct introduction of reused water into a public water system and the planned addition of reused water into a raw water source directly upstream of a water treatment plant, which elsewhere is known as indirect potable reuse.

Table 1. Governance frameworks for water reuse in Windhoek, California and Spain.

Windhoek	California	Spain
Technical guideline by the Department of Water Affairs, Ministry of Agriculture, Water, and Forestry (2000)	US Safe Drinking Water Act, 1974, amended in 1986 and 1996.	Revised text of the Water Law, Royal Legislative Decree 1/2001, of 20 July.
Standards for agricultural water reuse to issue permits.	California's Safe Drinking Water Act regulations	Royal Decree 1620/2007, of 7 December, and A.G.U.A. Programme (Actions for the Management and Use of Water).
Water Resources Management Act (Act 11 of 2013) for non-potable reuse in industrial, mining, agriculture and landscape.	Policy for Water Quality Control of Recycled Water adopted in 2009 and amended in 2013 and 2018.	National Plan for Water Treatment, Sanitation, Efficiency, Savings, and Reuse (2021) and 2030 Spanish Circular Economy Strategy
Water Resources Management Act (Act 11 of 2013) Regulations acknowledge water reuse for potable purposes.	Direct Potable Reuse Regulations (SBDDW-23-001)	Royal Decree-Law 4/2023, of 11 May, with climate mitigation and adaptation measures.
	California's Title 22 water reuse regulations (Cal. Code Regs. tit. 22) for groundwater augmentation applications.	Royal Decree 1085/2024, of 22 October, that approves the Water Reuse Regulations.

At its North Head WWTP, the Sydney Water Corporation, Australia, operates a 4.5 MW power station at the foot of the 60 m fall of primary treated wastewater into its deep ocean outfall. Sydney Water meets 21% of its total power requirements from a combination of 11 cogeneration plants at eight WWTP sites [18]. The corporation has developed solutions that are more cost-effective than mainstream options. Following the New South Wales Environment Protection Authority wastewater regulations, plants also produce reused water for agricultural, amenity, non-potable domestic and replacement environmental flow uses. A demonstration center for Purified Reused Water has been established at the Quaker's Hill WWTP [19], initially for agricultural and domestic (non-drinking) system use, but potentially suitable for direct potable consumption, built on the Australian National Water Quality Management Guidelines for augmentation of drinking water. Also in Australia, Yarra Valley Water operates a pilot hydrogen fuel production facility in association with its Aurora WWTP as an even broader approach to the circular economy. Combined with food waste co-generation, it provides the electrical energy for reverse osmosis to produce high-quality reused water for domestic non-potable use. The water and energy are also used in electrolysis to produce hydrogen for transport fuel use, and co-produced oxygen may be used to improve the efficiency of the WWTP system. Surplus electricity remaining can be fed to the grid [20].

4. Final thoughts

Worldwide, climate change and its growing impact on water resources are driving water utilities to move towards building resilience in their water supply to provide stable sources of clean water and mitigate social and economic impacts. Economically, water reuse reduces demand for freshwater, significantly decreasing expenditures of extraction or collection, treatment and distribution. It also alleviates operational pressure on wastewater treatment infrastructure, optimizing asset performance and deferring capital investments in system upgrades or expansion. Additionally, by diversifying water sources, it enhances resilience against supply disruptions, reducing economic risks during droughts or emergencies. Additionally, water reuse can create economic opportunities through innovations in recycling technologies and green infrastructure, while adhering to policy, legal and regulatory frameworks. Looking toward the future, more research is necessary on the possibilities to extend water reuse to locations that are not water scarce yet, as a form of preparedness to climate change.

Data availability statement

No new data were created or analysed in this study.

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