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One water – evolving roles of our precious resource and critical challenges

Veera Gnaneswar Gude

ABSTRACT

This article presents the evolving challenges and roles of our water resources in this contemporary world. First, water quality issues surrounding water supplies are discussed. Potential pathways to address the water quality challenges are presented, which include technological approaches for minimizing waste and enhancing resource recovery. Focused discussions on emerging global pollutants such as microplastics and PFAS (per- and poly-fluoro alkyl substances) and treatment alternatives are included. Next, the roles of used water (wastewater) in the wake of circular economy and recent outbreaks are discussed. The potential for energy and resource recovery possibilities and the critical role of wastewater treatment plants in controlling the spread of outbreaks are discussed in detail. Finally, perspectives on some of the key developments essential for transforming our water infrastructure, addressing water-centered socio-economic issues and the critical needs of digitalization in water sector operations are presented.

Key words | circular economy, infrastructure, microplastics, PFAS, resilience, water and wastewater

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HIGHLIGHTS

- Roles of water and wastewater in circular economy and community resiliency are discussed.
- Microplastics and PFAS and emerging issues in water and wastewater industry are discussed.
- Critical need for digitalization, data control and infrastructure investment are emphasized.

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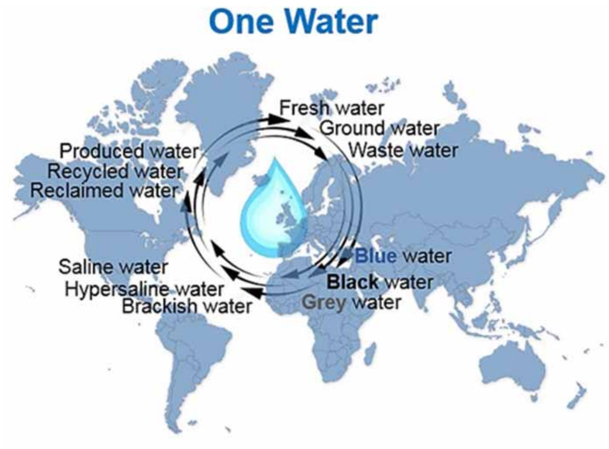
GRAPHICAL ABSTRACT



INTRODUCTION

The basic needs of sanitation and hygiene can never be overstressed and these cannot be met without the use of freshwater sources (Gude 2016a). Worldwide population growth and economic development coupled with higher living standards have escalated the global freshwater demands over the past few decades (Gude 2017). While the number of inhabitants increases, freshwater reserves at the global level remain finite, which need to be protected and preserved for longevity, so that the critical needs of our society can be met in a sustainable manner. It is estimated that by 2050, more than 5 billion will face water scarcity (WWAP 2018). At the global level, we have only one 'water' source whether it is called brackish water, freshwater, ground water, hypersaline water, saline water, seawater, surface water and 'used' or wastewater, which is impacted by climate change, irregular hydrologic cycles, excess withdrawals, and anthropogenic pollution (Figure 1). There is a pressing necessity to identify the trends of water supply demands, sources of pollution, and inadequacies in infrastructure and operations so that timely and effective remedies can be developed.

Global freshwater consumption has increased by eightfold over the past century, and the freshwater withdrawals have increased by threefold with respect to the population growth (Wada & Bierkens 2014; Gude 2018a). Several river basins and aquifers are under exploitation worldwide, which could impact the ability to provide freshwater sources to 25% of the world population in near future (Soligno *et al.* 2019). While groundwater is a critical resource for sustainable development in many regions of the world, overexploitation of the resource could lead to global water scarcity and other compounding issues related to people, economy and the environment (Gude 2018a; Huang *et al.* 2019; Gleeson *et al.* 2020).

The availability of water sources (quantity) will also affect the quality of the resource often impacted by human extraction and exploitation causing impairment of the resource. Ensuring water sources of adequate quality for beneficial uses is paramount to sustainable development. Enabling technologies should be developed to ensure high-quality and reliable water supplies. In recent decades, the water industry has been faced with several unprecedented challenges in meeting both the quantity and quality of water resources required for various beneficial uses and ecosystem protection. The purpose of this article is threefold: (1) to discuss and present management and technological approaches required for demand mitigation and supply enhancement in order to address both water quality and quantity issues, especially considering the ubiquitous nature of microplastics and PFAS; (2) to discuss the

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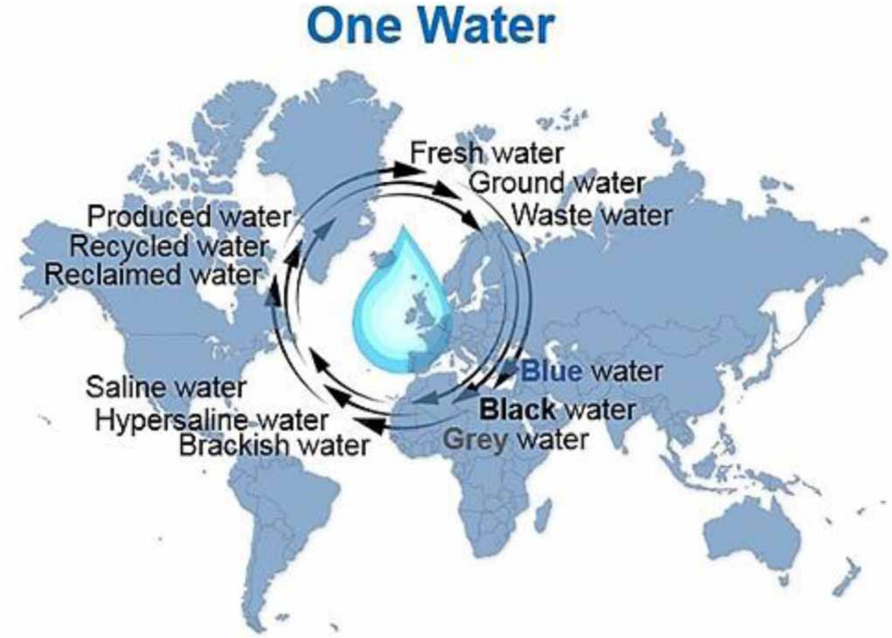

Figure 1 | One water concept – various forms, purposes and uses of water resources.

potential roles of wastewater treatment facilities in circular economy and outbreak control and management; and (3) to present some of the key developments essential to transform our water infrastructure, to address water-centered socio-economic issues and the critical needs of ensuring resiliency in water sector operations.

The purpose of this article is to discuss how we may progress from conceptualizing our wastewater treatment systems as waste management, to resource recovery and human health management systems. To do this, an overview of some emerging water quality issues and the state of the art of the treatment technologies by which they can be addressed is presented. The emerging role of wastewater treatment plants for informing public health policy regarding the SARS-CoV2 outbreak is discussed. Finally, some suggestions for focus areas that can lead to transformation of our water infrastructure are presented.

WATER QUALITY CHALLENGES

The major scientific and technological advancements in recent decades have led to the creation and production of numerous synthetic chemical and biological compounds that now pose a threat to our water sources in a number of ways. These include chemical and biological contaminants, pharmaceuticals and personal care products, metals, pesticides, and more recently, microplastics and PFAS (per- and poly-fluoroalkyl substances) as shown in Figure 2.

Considering current challenges faced by the water industry, the order of water pollutants in terms of their priority is listed as follows: PFAS, point and non-point source pollution, chemical spills and cyanotoxins, CSOs (combined sewer overflows), lead and copper from aging infrastructure, nutrient removals, pathogens, perchlorates, arsenic and radionuclides (AWWA 2020). While there has been a great deal of effort put into developing solutions for removing metals, pesticides, biological contaminants, and pharmaceuticals and personal care products over the past few decades, solutions are yet to be developed for emerging constituents such as PFAS and microplastics. PFAS rose to the top 2020 regulatory concern after placing second in 2019 and ninth in 2018. The USEPA (The United States Environmental Protection Agency) has proposed setting national drinking water standards for two of the most common and studied types of PFAS chemicals and is seeking comment on potential monitoring requirements and regulatory approaches for the chemicals. In the meantime, numerous

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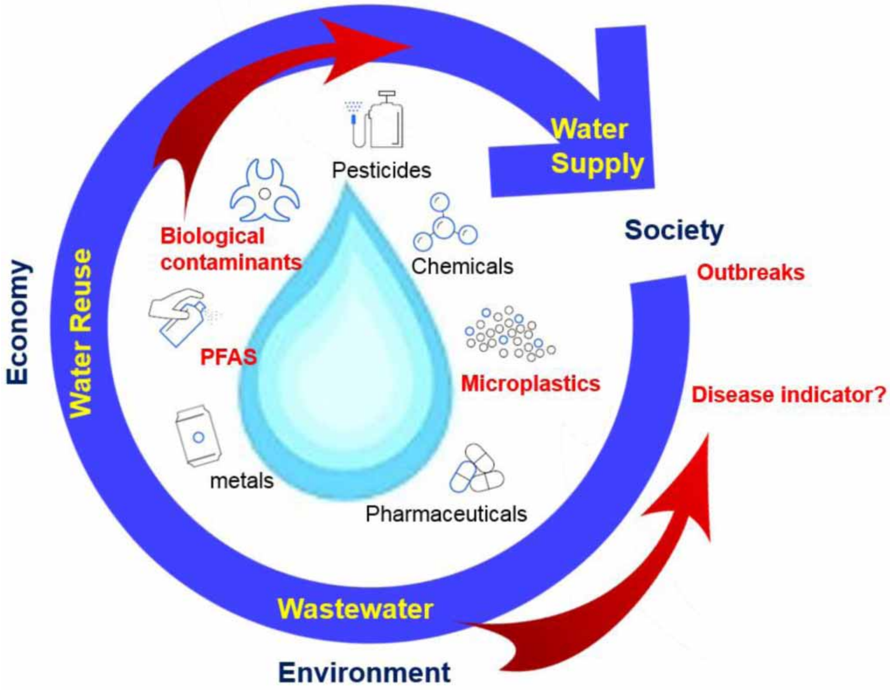

Figure 2 | Critical roles of water resources in circular economy and major emerging pollutants.

states have established or are considering PFAS regulations to be implemented in the near future (AWWA 2020).

Microplastics

'Microplastics' have become a major global pollutant even expanding into uninhabited territories such as Arctic and Antarctic regions. Almost all water bodies (surface and subsurface water bodies including oceans) and surrounding ecosystems are influenced by the presence of microplastics. It has been estimated that some 1,000–1,000,000 fibers are released from a single garment. Around 35% of microplastics occurring in oceans are from synthetic fibers and textiles (Prata 2018). In general, the plastic pollutants can be identified by their size as mesoplastics, microplastics, and nanoplastics (Andrady 2011). Spectroscopy and imaging can be used to identify the mesoplastic pollutants, while fluorescent techniques and microscopy can be used to analyze the presence of microplastics. Electron microscopy can be used to identify the presence of nanoplastics. Polymer identification methods including Fourier-transform infrared spectroscopy (FTIR), inductively coupled plasma mass spectrometry (ICP-MS), and Raman spectroscopy can be used to quantify microplastic particle (MP) concentrations in food sources and drinks (Cox *et al.* 2019).

Some of the pathways that may contribute to the degradation of microplastics in the environment are biodegradation, photodegradation, thermooxidative degradation, thermal degradation and hydrolysis. Solar-assisted UV degradation is a very efficient mechanism; however, it is significantly impeded by moisture or under water environment. Possible consumption of microplastics can lead to numerous health impacts (Cox *et al.* 2019).

Human consumption of microplastics is another evolving concern. Microplastics are present in various food sources and drinks including bottled water. The concentrations of microplastics vary across the sources. For example, seafood (fish, bivalves and crustacean) may contain 0–4.35 microplastics per gram; salt (lake, rock and sea salts) may contain 0–0.62 microplastics per gram; alcohol (beer) may contain 4–83 microplastics per liter; bottled water may contain 0.33–325 microplastics per liter and finally air in apartments, offices and outdoor environments may contain 0.3–24 microplastics per m^3 (Cox *et al.* 2019).

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Wastewater treatment plants receive effluents with high concentrations of microplastics. Primary, secondary and tertiary treatment schemes enable the removal of microplastics to a great extent, but a significant portion of these particles is discharged through effluents into the receiving environment. In regions where strict regulations are not maintained for secondary wastewater treatment, microplastics escape through the system (Prata 2018).

There are several methods to remove microplastics from the water sources. These include chemical (advanced oxidation, coagulation–flocculation, chlorination and electrocoagulation), physical (adsorption, granular sand filtration, sedimentation, ultrafiltration and reverse osmosis) and biological processes (anaerobic digesters, membrane bioreactors, activated sludge and other biological wastewater treatment units). The removal efficiencies of these processes depend on the chemical and physical characteristics of microplastics. There is a wide range of removal efficiencies reported for microplastics removal. These vary between 8 and 99.5% (Zhang & Chen 2020).

Some of the technologies capable of removing microplastics are not affordable. Low-cost and highly effective materials and methods should be developed for their removal. For example, biochar is presented to have a significant potential to immobilize and capture the microplastics (>95%) through morphologically controlled mechanisms providing superior performance to similar and conventional methods of filtration and separation processes (Wang *et al.* 2020).

Per- and poly-fluoro alkyl substances (PFAS)

Many toxic legacy chemicals have faded away in recent decades due to the enforcement of scientifically sound regulations by the regulatory agencies worldwide. However, there is a continuous flux of new chemicals that enters the environment, with the Chemical Abstract Service Registry growing from 20 million to 156 million chemicals between 2002 and 2019 (Lim 2019). As more chemicals of concern are revealed, the development and enforcement of new standards takes many years, sometimes decades, requiring a collective work of scientists, engineers, producers, regulators and end-consumers and community specialists to develop scientifically sound and practically feasible solutions to protect both humans and the environment. PFAS have become a recent threat to human health as they are perceived to be the cause for many health-related issues (Senthilkumar *et al.* 2007; Kwok *et al.* 2013; Domingo & Nadal 2019). A key feature of these compounds are the replacement of C–H bonds found in typical hydrocarbons with extremely strong C–F bonds, which limits biodegradation and other detoxification processes. As shown in Figure 3, more problematic 8-carbon substances (PFOA – perfluorooctanoic acid, PFOS – perfluorooctane sulfonate) have already been or are currently being heavily restricted in the manufacturing industry. However, the damage has already occurred due to the wide-spread use of these substances through various consumer products that span from agriculture to space applications (Clara *et al.* 2008; Brusseau 2018; Zhu & Kannan 2019). As fluoro-chemical manufacturers switch to 6-carbon (Gen X) and 4-carbon (PFBA – pentafluorobenzoic acid) chemistry, different impacts are observed as new persistent PFAS enter the water system (Hopkins *et al.* 2018). The numerous pathways through which humans are exposed to PFAS regardless of the living environment are shown in Figure 3. USEPA has recently implemented a task force to study the presence of PFAS in urbanized communities (or community water systems serving >10,000 people), but more has yet to be discovered regarding their presence in agricultural and rural communities, which support local and national economies in numerous ways.

Conventional drinking water treatment (coagulation, flocculation, lime softening and sand filtration) and biological wastewater treatment (activated sludge including anaerobic digestion) schemes are not capable of removing these substances successfully (Ross *et al.* 2018). Moreover, biosolids and their land application has become another concern due to the presence of high concentrations of PFAS. Very high concentrations of PFOS and PFOA (990 and 241 ng/g, respectively) have been reported to be present in biosolids (Venkatesan & Halden 2013; Gallen *et al.* 2018; Moodie *et al.* 2021). Advanced separation techniques such as ion exchange and membranes have shown comparatively better performance in removing these substances, but these processes usually generate a concentrated stream (Woodard *et al.* 2017). Sorption using highly active carbon surfaces seems to be a promising alternative, but this technique is not able to capture short-chain PFAS which is another concern. Advanced oxidation and reduction

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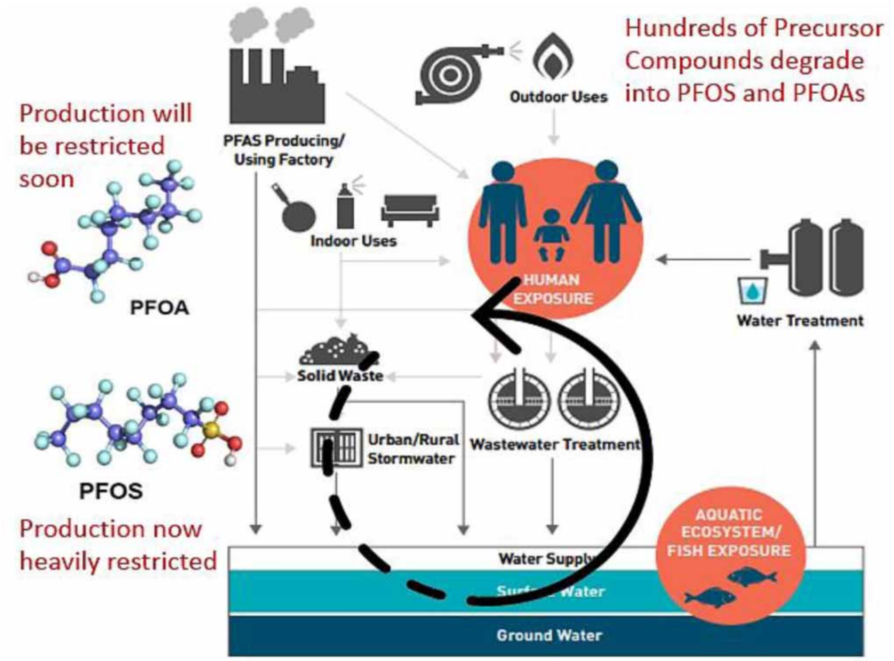

Figure 3 | Types of PFAS, their production status and human exposure to PFAS in various environments (The Water Research Foundation 2019).

processes were also explored equally for efficacy in breaking down of these substances. High thermal, high pressure and high radiation and sonic frequency treatment methods also have been carried out (Ross *et al.* 2018; Kundu *et al.* 2021). All of these have some degree of removal capacity but each with their own drawbacks such as high capital costs, low treatment volumes and high-specific energy consumption and residual products.

There are many technologies that can be employed for PFAS removal from water supplies and wastewater sources. These are classified as 'demonstrated', 'partially demonstrated' and 'developing' depending on their level of readiness for wide application. Demonstrated technologies include adsorption (activated carbon, granular-activated carbon and -reactivated carbon).

In granular-activated carbon system, the performance of the system is site-specific (McCleaf *et al.* 2017). Short-chain PFAAs break through sooner than longer-chain PFAAs. Similarly, carboxylates (PFCAs) break through faster than sulfonates (PFSAs). Activated carbon material can be 'reactivated' under high temperatures for reuse. Off-gases should be treated. Reactivated carbon is typically used in wastewater and groundwater remediation applications. Reactivation standards set by AWWA (B605-13) should be followed for drinking water applications.

Ion exchange is another proven technology for removing PFAS from water sources (Woodard *et al.* 2017). This technology is effective and requires smaller footprint compared with other options. The performance of this method is affected by other binding contaminants and competing dissolved solids. Sorption of PFAS varies between carboxylates and sulfonates. Used resin beds can be regenerated by using brine solution. Media contaminated with PFAS can be incinerated for complete destruction. Technologies are under development for treating low-volume, high concentration brine waste.

Reverse osmosis is a membrane separation process capable of separating PFAS both at high and low pressure operations (Tang *et al.* 2007). The performance varies with the type of membrane, and reject water needs disposal (Horst *et al.* 2018). This process also removes potentially beneficial constituents such as hardness, minerals and nutrients. Under partially demonstrated technologies are biochar sorption, zeolites/clay minerals, carbon/clay mixtures, coagulation/flocculation, and foam fractionation, electrochemical oxidation – destruction, and plasma treatment. Under

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developing technologies, advanced oxidation–reduction processes such as activated persulfate (oxidation), zero valent metals (reduction) and ultraviolet light + sulfite (red-ox), photolysis, e-beam, and sonolysis show promise for efficient treatment.

While we develop new technologies to eliminate PFAS from water supplies, it could be financially burdensome to implement or reconstruct the water supply infrastructure. Therefore, innovative (hybrid or integrated approaches involving separation or destructive technologies) solutions that provide extensive barriers with minimum retrofitting needs would be ideal for moving forward with future water treatment systems. The removal of PFAS is also highly influenced by the other water quality characteristics including competing chemical reactions and secondary water quality standards. Some of the destructive technologies discussed above show great promise for future development. However, techno-economic and energy and environmental performance indicators should be evaluated. It would be ideal to couple PFAS removal with energy or resource recovery schemes. For example, the aforementioned PFAS's presence in biosolids can be addressed by considering thermal degradation processes such as pyrolysis which can convert the biosolids into biochar while destructing the PFAS compounds in the pyrolyzer. This is a win-win situation for environmental remediation and resource recovery (Kundu *et al.* 2021).

Disinfectants for biological contaminants

Yet another emerging area of concern is the microbial contamination of drinking water supplies. Drinking water distribution systems are susceptible to microbial fouling due to water stagnation or suspension in water lines (Ling *et al.* 2018). It is reported that the number of microbial cells could range from 10^6 to 10^9 per liter (Hull *et al.* 2019). An estimated 39 billion gallons of water are withdrawn on a daily basis to supply the populations in the United States (Maupin *et al.* 2014). The source water is then treated through various conventional or advanced treatment processes before it is supplied to the communities through more than two million miles of distribution networks, and premise plumbing in buildings before delivery. Antibiotic-resistant bacteria and antibiotic-resistance genes have become major challenges as these can be spread through drinking water. Disinfection processes such as chlorination, ozonation, UV radiation and their combinations have been well studied. However, chlorination has been reported to enrich antibiotic-resistance genes in microorganisms (Zhang *et al.* 2019). Recent studies attempt to understand the antibiotic-resistance development during disinfection regimes at different locations (Han *et al.* 2020) and in groundwater sources (Poghosyan *et al.* 2020). It was also shown that the ozone-chlorination disinfection scheme has high abundance of antibiotic-resistance copies (Zhang *et al.* 2019). This indicates that the pathogenic microorganisms can proliferate and cause public health issues in water distribution networks (Haig *et al.* 2020). More research needs to be done to understand the evolution of antibiotic resistance in different disinfection regimes and in various sections of drinking water treatment and distribution networks. In addition, operation and maintenance procedures should be developed to avoid risks at the treatment plant, in distribution and in end-user facilities (Hozalski *et al.* 2020).

EVOLVING ROLES OF WATER SOURCES

Used water (also known as wastewater)

The amount of wastewater (used water) generated at community levels is in proportion to the water usage by the community. The used water should be treated to remove the pollutants and recover the resource. Physical, chemical and biological processes employed in primary and secondary treatment schemes enable this goal to be achieved, while the secondary (biological) treatment is mandatory and enforced as a standard to protect the environment and public health. With the realization that the discharged used water is going to interact with potential water supply sources in space and time across the regions, it is critical to ensure proper treatment of the used water to protect the water supplies. Energy-efficient and cost-effective treatment processes for the removal of major nutrients (carbon, nitrogen and phosphorus) and other deleterious compounds are being developed on a continuous basis to meet the evergrowing challenges of protecting our environment and receiving water bodies.

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Used water valued as a resource

The roles of wastewater treatment plants are evolving recently in different directions that require dynamic shifts to accomplish the new goals and objectives surrounding the performance of these facilities. For example, once considered as facilities to prevent pollution of receiving water bodies, these facilities are now valued as resource recovery facilities. Specific energy consumption of used water depends on its characteristics, quantity and treatment scheme, and the energy demand for used water treatment can be burdensome at times (Gude 2015). However, used water is now increasingly recognized as a valuable resource for water, energy and nutrients and other valuable bio- or energy-products (Gude 2016b). The energy embedded in the organic matter of used water is a motivating factor for potential energy recovery. Nutrients such as nitrogen and phosphorus are other valuable commodities required in agricultural and irrigation applications. Above all, water itself is a major and invaluable resource that could be recovered from these operations.

Used water treatment facilities also play an important role in so called circular economy advancement. Sustained growth of resource consumption and subsequent depletion has led to the development of new philosophies such as 'circular economy' which limits the fresh resource consumption and promotes resource recovery and recycling (Ghisellini *et al.* 2016; Corona *et al.* 2019). Anaerobic digesters play an important role towards implementing circular economy principles by recovering valuable energy and bio-products (Hussain *et al.* 2020). Codigestion of fats, oil, grease and other organic wastes with sludge has received significant interest in recent years (Sarpong *et al.* 2019, 2020; Sarpong & Gude 2021). There are other alternatives to transform sludge generated in used water treatment plants into valuable energy-products through thermochemical processes such as gasification, pyrolysis and supercritical water processes, but anaerobic digestion has shown the highest practical feasibility worldwide in various applications (Gude 2018b; Gherghel *et al.* 2019).

Based on the above discussion, used water can be classified to have three important elements, water, energy, and nutrients, these can be efficiently harvested and recycled or reused. Technological readiness of each of the recovery options determines the level of circularity that can be achieved for each component. For example, the anaerobic digestion alone can provide up to 50% of energy recovery. This recovery rate can be enhanced to 60–70% with the use of combined heat and power systems. Similarly, depending on the end-use applications, wastewater can be treated to remove organic compounds and nutrients and the effluent can be purposely utilized. The amount of wastewater that can be reused depends on its quality and other parameters. In addition, technology affordability (e.g., granular-activated carbon filter vs. membrane technology) is critical to the successful recovery of the resource. Finally, the cost-effectiveness of nutrient recovery technologies depends on the wastewater characteristics and the recovery method. The following circular economy indices can be written for each of these elements. In this example, only three elements are considered. It is possible to consider streams such as solids and other valuable waste derived chemicals.

While there are many ways of defining circularity (Saidani *et al.* 2019; Linder *et al.* 2020), circular economy index of water source ($\mathrm{CEI_W}$) in wastewater can be written as (Kiselev *et al.* 2019):

$$\mathrm{CEI_W} = \frac{\mathrm{W_R}}{\mathrm{W_T}}$$

Here, $\mathrm{W_R}$ is the amount of water that is recovered or recycled, and $\mathrm{W_T}$ is the total wastewater that was treated in the wastewater treatment plant.

Circular economy index of energy source ($\mathrm{CEI_E}$) in wastewater can be written as:

$$\mathrm{CEI_E} = \frac{\mathrm{E_R}}{\mathrm{E_W}}$$

Here, $\mathrm{E_R}$ is the amount of water that is recovered and $\mathrm{E_W}$ is the total energy content in wastewater that was treated in the wastewater treatment plant.

Circular economy index of nutrients ($\mathrm{CEI_N}$) in wastewater can be written as:

$$\mathrm{CEI_N} = \frac{\mathrm{N_R}}{\mathrm{N_W}}$$

Here, $\mathrm{N_R}$ is the amount of nutrients that is recovered or recycled and $\mathrm{N_W}$ is the total amount of nutrients in wastewater that was treated in wastewater treatment plant.

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Total circular economy index:

$$\mathrm{CEI_T} = \frac{\sum_{i=1}^{n} \mathrm{CEI}_i}{n}$$

Here, CEI_i represents the CEI of each component, and n stands for the number of elements that could contribute to the circular economy of the wastewater.

Based on this mathematical formulation, the total circular economy index can be calculated as a fraction of the maximum value possible which is 1. For example, as mentioned before, there is no possibility to recover 100% of energy present in the organic content and thermal source of wastewater. The same applies to nutrient recovery. However, water recovery can be achieved to the maximum extent and up to 95% of water recovery may be possible. Considering the current status of circularity in wastewater treatment plants, most of the wastewater treatment plants currently present a circularity between 0.1 and 0.25 (see Figure 4). It does not mean that higher circularity values are not possible. They can be achieved only with advanced technology implementation and by repurposing the resources recovered from wastewater to the maximum extent possible. For example, energy recovery up to 75% is possible and similar, or higher recovery rates are possible for water reuse. Together, water and energy or valuable bioproduct recovery may increase the circularity to 0.5–0.75 (or 75%). Finally, beneficial sludge utilization may help further improve the circularity.

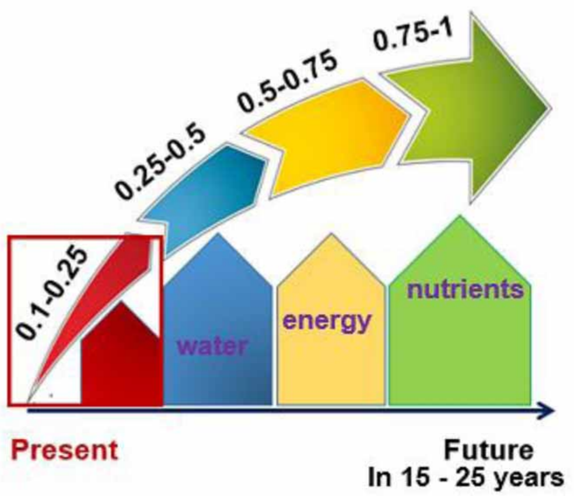

Figure 4 | Used water circularity status – present vs. future (in 15–25 years).

Used water circularity can be improved by using low-energy demanding technologies for wastewater treatment such as algal-based wastewater treatment and wetlands. Wetlands provide numerous environmental as well as socio-economic benefits. A variety of pollutants can be efficiently removed in wetlands (Ghimire *et al.* 2019; Martinez-Guerra *et al.* 2020). Similarly, algal-based wastewater treatment holds high potential for enabling energy-efficient and cost-effective wastewater treatment (Blair *et al.* 2014; Otondo *et al.* 2018). Most of the technologies are already well known and established, and further improvements in efficiencies will help improve used water circularity.

Still some other technologies are on the horizon having potential to address the water-energy nexus of the used water treatment. These are based on the unique characteristics and bioelectrochemical behavior of certain exoelectrogenic bacteria. The systems include electroactive biofilms (on electrodes in the anode and cathode compartments) which allow for electron generation, transfer and harvest in a configuration called microbial fuel cells (Logan 2008; Gude 2016b, 2018b). The outstanding advantage of this method is that there is a possibility to convert the waste (organic matter, other metals and nutrients) present in the used water to clean electricity directly, although there are many challenges to be overcome. Recent studies also demonstrated recovery of electricity and struvite (fertilizer) from human urine by using artificial seawater as magnesium source (Merino-Jimenez *et al.* 2017; Liao *et al.* 2020). There are many variations of this technology, the main technologies being microbial electrolysis and microbial desalination cells (Gude 2016b). Microbial desalination cells, in particular, allow for recovery of clean electricity, waste removal and saline water pretreatment, all in a single configuration, facilitated by the ionic imbalance, osmotic pressure differences, and microbial biofilm activities (Kokabian & Gude 2013, 2015). Microbial fuel cells and microbial desalination cell technologies can be developed in various configurations which many include abiotic and biotic cathodes, different types of membranes, and different microorganisms and electrode materials (Ghimire *et al.* 2021).

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Wastewater treatment plants as disease surveillance facilities

The spread of COVID-19 disease has presented unprecedented challenges in recent times (Gude & Muire 2020) affecting productivity across all sectors. Water and used water treatment plants are not an exception. These facilities can be used as microbial (virus) observatories for disease surveillance and for testing the presence of SARS-CoV-2 in the influents (Sims & Kasprzyk-Hordern 2020; Schmidt 2020). This can serve as a key to estimate the general health status of a community and determine any hotspots for preventive measures. Numerous scientists and research groups are currently investigating the origin, transmission, and clinical therapies for addressing the COVID-19 and datasets are being generated (Guo *et al.* 2020). Research should be continued to develop ways through which the methods commonly used for sampling and concentration of enteric, non-enveloped viruses from water environments can be successfully adapted (La Rosa *et al.* 2020).

Wastewater-based epidemiology is increasingly recognized as a complementary approach for infectious disease surveillance and early warning system for disease outbreaks (Daughton 2020; Orive *et al.* 2020; Sims & Kasprzyk-Hordern 2020). The presence of virus (viable and non-viable particles) can be quantified by targeting virus functional or structural motifs in wastewater (Daughton 2020). Detection methods such as qPCR, RT-PCR and ELISA coupled with the most probable number (MPN) method can be employed for quantifying the virus's presence. Well-established quality analysis and quality control methods/procedures should be followed to account for sensitivity, error analysis and to ensure uniformity across the datasets from different research groups to further facilitate the process of validating and developing procedures. In some cases, analysis could be hindered by detection limits. As the population and demographics (customer profiles) vary for each utility, monitoring and tracking is important to establish temporal and spatial patterns. Location and time of sample collection in addition to the wastewater strength and stage of treatment will be critical in understanding the importance of the results. Normalization of data is important for ranking community-wide infection rates to develop better-informed intervention measures and the prevention of emergency situation. This quantification also allows the estimation of chemical requirements and resource needs at utilities. Care must be taken as reporting average log reductions of pathogens could also lead to large misrepresentation and misunderstanding of both data and results (Schmidt *et al.* 2020).

SARS-CoV-2 provides numerous opportunities to learn, discover and collaborate with other scientists for better understanding of the preparedness and response schemes from local, regional and national settings. Wastewater utilities can develop sample repositories nationwide to conveniently derive information on the occurrence and identification of SARS-CoV-2 as well as their persistence and propensity to withstand degradation processes. It is possible that the virus may develop resistance to the oxidation and other removal processes. This information can be shared among the utility sector stakeholders to better understand the prevalence of virus in different wastewaters in an effort to protect human society and the environment (Gude & Muire 2020).

Recent studies and surveillance programs in many countries across the world have confirmed the genetic traces of SARS-COV-2 and correlations of the disease trends in communities. For example, in the USA, a company is analyzing samples from 400 treatment plants across the country on a twice-a-week basis. There are many unknowns and uncertainties in these procedures. A recent report outlines three important steps to effectively predict the outbreaks based on wastewater samples (Xagoraraki 2020). Another study focused on predicting the socio-economic status of the population by using biomarkers in wastewater (Choi *et al.* 2020). These studies reveal possible venues for wastewater-based inventions. New variants have also been reported recently, and these have become the cause for new surges in infections around the world. In view of all these trends, more research efforts should focus on developing standard protocols and provide robust and reliable estimation tools (Schmidt *et al.* 2020).

Future scenarios for water technologies

New technologies, in general, are hyped in their potential for their performance, usually in an effort to increase their visibility (see Figure 5(a)). However, their actual

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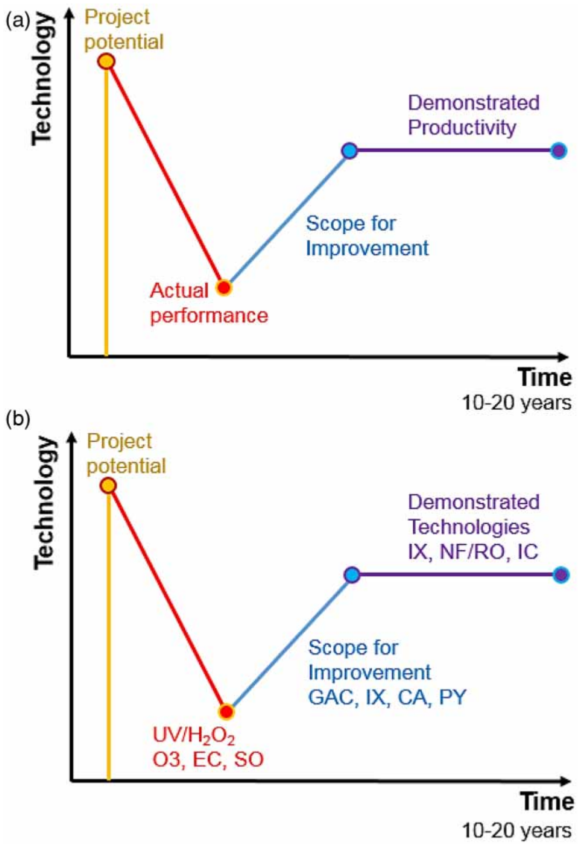

Figure 5 | (a) Typical technology development profile toward commercialization and (b) the status of currently available technologies for PFAS removal from water and solids (CA, chemical addition; EC, electrocatalytic process; GAC, granular-activated carbon; H_2O_2, hydrogen peroxide; IC, incineration; IX, ion exchange; NF, nanofiltration; O_3, ozonation; PY, pyrolysis; RO, reverse osmosis; SO, sonolysis).

performance may be significantly lower than the expected or project potential. This is called actual potential or performance. This stage clearly provides an opportunity for realization of actual and practically feasible technological potential and the scope for improvements can then be determined. Further efforts of redesigning and improving the process performance will enable the practical and demonstrated potential or productivity of the new technology for market advancement and commercialization for wide applications. Water technologies are not different from other industrial technologies in this sense and essentially follow the same trend. It may take about 10–20 years for a new water technology to advance to commercialization stage from the point of conceptualization. For example, Figure 5(b) shows the status of various technologies used in their potential for removing PFAS from water sources. It can be seen that some of the technologies are performing at much lower level than the expected or project potential, while others have advanced to the improvement stage and some others have finally reached the demonstration and commercialization stages. Those technologies that are under development may take 10–20 years before they can be implemented in the water industry. Many factors such as cost-effectiveness, process safety, byproduct formation potential, residual products and concentrates generated through the treatment process provide ongoing challenges for full development of each of these technologies. Further, new technologies need to be tested and demonstrated in the field and they need to prove the requirement for regulatory standards over a period of time to include potential margin of safety and expected performance variances to be fed back into redefining the regulatory standards.

WHAT ELSE DO WE NEED MOVING FORWARD?

Under ‘one water’ concept, water and used water interact in hydrological cycles. Therefore, there should be a proper coordination between the water supply and used water management sectors to enable efficient resource recovery, human health protection and waste management. Within the water sector, water and wastewater (used water) utilities operate independently and coordination between the two utilities is lacking in many municipalities. There is a growing importance and need for improving communication between different utilities to protect water sources. In addition to effective communication and coordination, other critical areas where significant efforts are warranted to make a holistic difference in this sector are aging infrastructure, dwindling workforce, inefficient process control, and socio-economic differences. These challenges will be discussed next.

Investing in water infrastructure and workforce

Aging infrastructure has become a major issue in many developed countries (Sakai *et al.* 2020). Utilities recognize the critical need to invest in infrastructure improvement projects. Still, their limited resources require striking the right balance between addressing emerging needs and executing

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repair and rehabilitation of existing assets. Having a well-defined asset management and assessment program in place allows utilities to analyze systems for vulnerabilities and catastrophic failures and mitigate those risks in a balanced and proactive way. America's water infrastructure is deteriorating quickly, causing increasing failures because adequate investments have not been made in rehabilitation or replacement over the past few decades. Several performance indicators have been used to measure the status and performance of water and wastewater infrastructure which are based on cost-effectiveness, customer satisfaction, system management, condition, and reliability, infrastructure stability, and financial viability. Nearly 80 percent of the water, wastewater and stormwater professionals responding to a survey named aging infrastructure as the most challenging issue they face today. Many also report that the experienced workers who have kept their water flowing for decades are reaching retirement age. These dual problems are forcing utilities to focus on asset management, shift hiring practices and adopt new strategies for the workforce of tomorrow.

Investment in water sectors should be viewed as an economic endeavor as many industries and business operations are severely impacted by the lack of water supplies and wastewater management services even with short-term interruptions (Gude & Muire 2020). Investing in water infrastructure is the first step towards sustainable economic development. Therefore, used water treatment system investments should be directed more towards revenue-generating schemes where these systems are recognized as key resource recovery facilities and contributing factors towards better economy. This means that future used water treatment systems will be designed to enhance water, energy, nutrient and economic circularity in communities via non-conventional biological, chemical, physical and thermal processes and integrated configurations. For example, in future systems design, different sources of used water may be separated at source for efficient resource recovery. As explained earlier, if human urine can be separated at the source, there is significant potential for recovering nutrients present in it for further beneficial uses. This step also improves the efficiency of downstream processes. Similarly, algal treatment systems and wetlands are being considered favorably in many new developments. All these facts mean that workforce should be constantly trained and equipped with critical skills required to accomplish this transition towards more efficient and resource recovery system design and operations.

Digitalization and data management

To increase efficiency and productivity across all (water, energy, chemical and manufacturing industry) sectors, water utilities should first be updated because most of these essential services cannot be provided without the aid of freshwater supplies and proper management of used water (Gude & Muire 2020). Digital transformation (i.e. automation, digital control and dynamic resource optimization schemes) is critical to enhance efficiency and productivity which cannot be obtained by implementing a single technology. An array of technologies including field sensors, communication networks and computer models and assessment software, remote control systems such as SCADA (supervisory control and data acquisition), geographic information systems (GIS), flow and/or water quality data analysis, computerized maintenance management systems (CMMS) and operations management systems (OMS), as well as customer information systems (CIS) are required to develop customized solutions. The right combination of these technologies, when properly integrated, will fuel digital water transformation.

The use of data management is very important in estimating the equipment failures and potential costly outages in water utility operations (Eggimann *et al.* 2017; Ghernaout *et al.* 2018). Emerging tools such as artificial intelligence may provide predictive analytics from the point of view of potential failures and aging infrastructure (Bakalos *et al.* 2019). Data and technology driven innovations can help predict and monitor or control the behavior of energy and chemical supply systems in water utilities (Clark *et al.* 2017). Data-based planning will eliminate losses and improve efficiencies in various stages of the water utility operations.

Socioeconomics and water resource education

The effects of changes in social and economic factors, such as population growth and water consumption, might be as important or even more important than climate change in

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affecting the hydrological cycle and increasing water scarcity risk (Koutroulis *et al.* 2019). There is a significant imbalance in the origin of the blue water (fresh surface and ground water sources) increasingly consumed by developed and developing countries. On average, developed (economically advanced) countries tend to increase their affluence by intensifying mainly the use of foreign water resources; conversely, the affluence growth in developing regions mostly relies on the use of local water resources. As a matter of fact, despite the water resource status, developed economies are becoming increasingly reliant on developing countries (or economies) for supplying blue water-intensive commodities (Soligno *et al.* 2019). Similarly, virtual water transactions have become inevitable for global trade and prosperity. This means that already resource-constrained regions may be put to stress to meet the growing demands in other regions in order to maintain the economy.

Water reuse implementation issues vary from size to size. Decentralized and small communities face different sets of problems when compared with medium- and large-size communities. Economics and perceived benefits are not encouraging at small community levels, whereas complex regulatory and implementation issues arise for medium- and large-size communities. Public education about the value of water and adverse effects of water impairment and water scarcity will help implement some of the management strategies for demand mitigation. Governance and financing the clean water and environment initiatives can aid to implement a long-term sustainable freshwater supply system in drought-influenced regions. However, there are limited data available on the effectiveness of publication education and outreach programs in improving water conservation and reuse. More comprehensive studies involving quantitative and qualitative analysis are required to determine whether how and what educational programs are more effective in promoting the water conservation ethic.

There has been a continued interest in understanding the disparities between water infrastructure and the quality of services provided to communities that are categorized as socially different or unique (Apul *et al.* 2021). Environmental and water resource engineers and scientists have an important role in demystifying some of the perceptions related to the technologies and their capabilities, scientific discoveries and their practical relevance and associated regulations and policies (Hicks *et al.* 2021). Water quality and quantity-related challenges can be complex when they are tied up with socio-economic statuses of certain communities. Care must be taken when addressing these challenges through creative and conscientious environmental solutions.

Finally, education and outreach efforts should address the issues at the nexus of the consumers, manufacturers, regulators, stakeholders, investors, and water utilities. Individual choices that lead to water pollution, utility owner preferences that impact water system designs and regulatory enforcement of effluent and water supply standards and ultimately, the financial derivatives and investment interests should be revisited to understand the evolving roles and then overcome the challenges of our precious resource.

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DATA AVAILABILITY STATEMENT

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

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