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Water reuse from a circular economy perspective and potential risks from an unregulated approach

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Abstract

Considerations including water scarcity in arid and semi-arid regions, water security concerns in areas where water demand exceeds water availability, and rigorous and costly requirements to remove nutrients and emerging contaminants from effluent discharge to surface waters have driven water reuse as an alternate water supply in some parts of the world. However, the potential of reusing treated wastewater has not yet been exploited in many areas. A transition to a circular economy could create significant synergies for the wide adoption of water reuse as an alternate water supply. This paper therefore examines opportunities and risks with the transition to such an economy. Findings show that although many of the barriers water reuse is facing, ranging from public perception to pricing and regulatory challenges, could be addressed more effectively through a wider circular economy perspective, care must be taken with regulating and monitoring levels of contaminants in the recycled water according to its use. A review of existing reuse schemes and regulations across the world, found variation, demonstrating the need for assessing benefits and risks on a case by case basis. Recycling and reuse are central to a circular economy approach and offer a strategy to improve water supply by managing wastewater better. Such strategy should also ensure the safety of water reuse, and therefore apply water quality standards appropriate to the specific use, but also ensure adequate and reliable operation of water reuse systems and appropriate regulatory enforcement.

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Introduction

Water is essential for human survival and well-being and plays an important role to many sectors of the economy. However, water resources are irregularly distributed in space and time, and they are under pressure due to human activity and economic development [34]. Accelerated urbanization and the expansion of municipal water supply and sanitation systems also contribute to the rising demand [72]. Furthermore, climate change scenarios project spatial and temporal variations of water cycle dynamics, which exacerbate the discrepancies between water supply and demand [31,72]. Water for irrigation and food production constitutes one of the greatest pressures on freshwater resources, with agriculture accounting for over 70 per cent of global freshwater withdrawals and up to 90 per cent in some fast-growing economies [72]. Projections for biofuel production indicate that if by 2030, 5 per cent of road transport is powered by biofuels (the EU target is 10 per cent by 2020 [23]), this would amount to at least 20 per cent of the water used for agriculture globally [7]. Industry is also a major water user, accounting for between 10 per cent (Asia) and 57 per cent (Europe) of total water consumption [32]. Water (availability/scarcity/management) is one of the top global risks according to a World Economic Forum Global Risk Report [81]; estimating a 40 per cent shortfall in water supply globally at 2030, if no changes are made in how water is managed.

Apart from being an essential requirement for human survival and a fuel for economic development, water is also fundamental for sustainable ecosystem services [71]. The Earth's ecosystems could not function without adequate supplies of water of suitable quality. However, every time humans access, develop, transport or utilise water resources, they leave an impact that may degrade the service provided by the river, lake, wetland or groundwater aquifer supplying the water [46]. By increasing the concentration and the ecological effects of pollutants, water scarcity is a key stressor in many river ecosystems as it tends to exacerbate the detrimental effects of other stressors [58].

Water scarcity is particularly important in semi-arid regions such as the Mediterranean area [29,48], but also in other regions where water demand approaches or even exceeds, water availability. This includes large areas of Europe, as presented in the Water Exploitation Index (WEI), defined as the ratio of all annual abstractions over inter-annual resources [4,29]. Two thirds of the world's population currently live in areas that experience water scarcity for at least one month a year, meaning that about 500 million people live in areas where water consumption exceeds the locally renewable water resources by a factor of two [73].

The availability of water resources is also intrinsically linked to water quality, as the pollution of water sources may prohibit different type of uses. Increased discharges of untreated sewage, combined with agricultural runoff and inadequately treated wastewater from industry, have resulted in the degradation of water quality around the world [19]. If current trends persist, water quality will continue to degrade over the coming decades, particularly in resource-poor countries in dry areas, further endangering human health and ecosystems, contributing to water scarcity and constraining sustainable economic development [73]. In all but the most highly developed countries, the vast majority of wastewater is released directly to the environment without adequate treatment with detrimental impacts on human health, economic productivity, the quality of ambient freshwater resources, and ecosystems [73].

As freshwater supplies become more limited and economic development comes with increasing water demand, technologies such as desalination and water reuse are often recognised as solutions with a great potential in reducing the gap between availability and demand [41]. However, on a larger scale, brine released from desalination plants includes chemical residues that negatively affect coastal ecosystems [14]. Furthermore, although desalination may solve the problem of water scarcity in water stressed areas, there still lies the problem of associated wastewater management and the costs involved [41]. Continued failure to address wastewater as a major social and environmental problem would also compromise other efforts towards achieving the 2030 Agenda for Sustainable Development [73].

The ability to reuse water, regardless of whether the intent is to augment water supplies or manage nutrients in treated effluent (also a factor leading to water reuse), has positive benefits that are also the key motivators for implementing reuse programs [21]. These benefits include improved agricultural production; reduced energy consumption associated with production, treatment, and distribution of water; and significant environmental benefits, such as reduced nutrient loads to receiving waters due to reuse of the treated wastewater [33]. In Europe, the implementation of the Urban Waste Water Treatment Directive (91-271-EEC) has already contributed to obtain treated wastewaters of quite high quality that could be reused for certain applications or improved by polishing steps for uses with higher quality requirements [24].

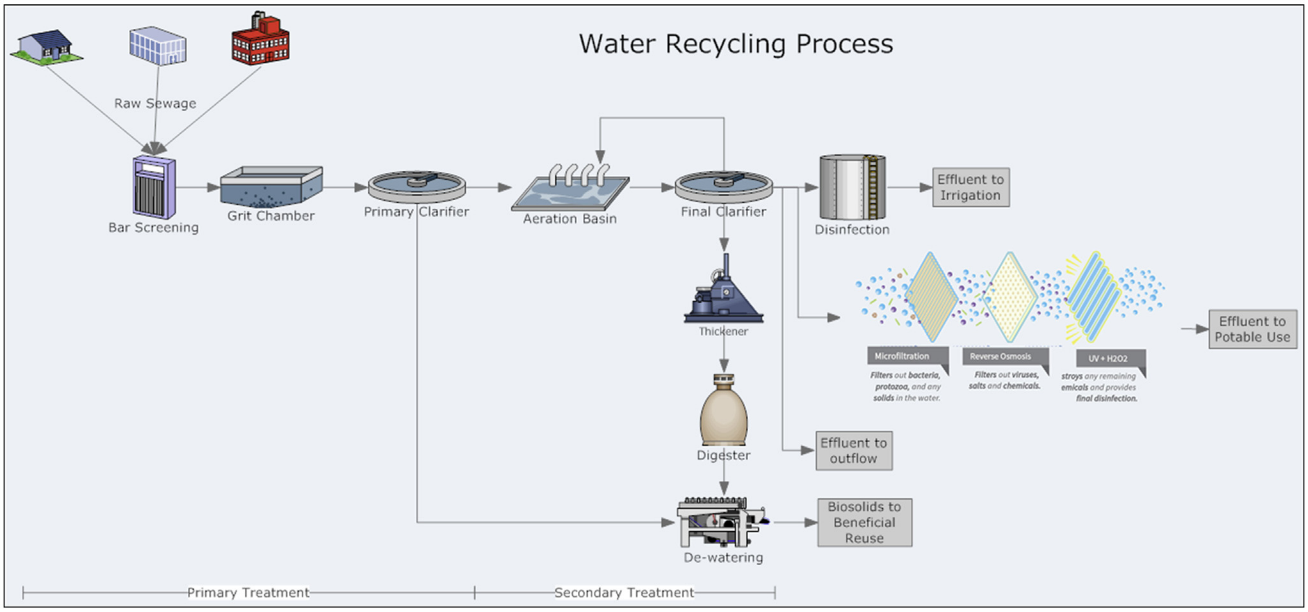
Even though reclaimed water reuse is currently implemented in many countries, its potential has not yet been exploited in many areas, and the proportion of water reuse in total wastewater generation is still small. However, this is changing. Global water reuse capacity was estimated to have risen from 33.7 GL/day in 2010 to 54.5 GL/day in 2015, with the largest growth in China, the United States, Middle East, North Africa, Western Europe, and South Asia [8]. With a transition to a *Circular Economy* this rise would further accelerate. This emerging worldview that considers that a third industrial revolution is underway, supported by the age of the internet that facilitates the exchange of ideas at a pace never seen before, sees many states beginning to use their financial and regulatory capacity to kick-start a circular economy that could create significant synergies for the wide adoption of water reuse. The concept has emerged in response to drawbacks of the conventional 'take-make-consume and dispose' model of growth and the shift towards sustainable development. This paper therefore examines water reuse from a circular economy perspective and investigates opportunities and risks for water reuse with the transition to such an economy.

Wastewater treatment and water reuse

Conventional sewage treatment (Fig. 1) starts with preliminary screening and grit removal, intended to remove the larger floating and suspended materials that could interfere with the treatment process [38]. Primary sedimentation follows and removes approximately 55 per cent of the suspended solids and because some of these solids are biodegradable the biochemical oxygen demand (BOD) is typically reduced by 35 per cent. Then, secondary treatment usually involves a biological process. Microorganisms in suspension (in the "activated sludge" process), attached to media (in a "trickling filter" or one of its variations), or in ponds or other processes are used to remove biodegradable organic material. In the activated sludge process the majority of biological solids removed in the secondary sedimentation tank are recycled (returned sludge). The feedback of most of the cell yields from the sedimentation tank encourages rapid adsorption of the pollutants in the incoming settled sewage and also serves to stabilize the operation over a wide range of dilution rates and substrate concentrations imposed by fluctuations in the flow and strength of the wastewater. Secondary treatment processes can remove up to 95 per cent of the BOD and suspended solids entering the process, as well as significant amounts of heavy metals and certain organic compounds which could otherwise cause the deterioration of chemical and ecological quality of receiving waters [10,53]. Conventional wastewater treatment usually ends with secondary treatment which cannot efficiently remove all the different compounds found in sewage and therefore treated effluents are one of the main sources of persistent micropollutants in the environment [1,62].

For water reuse, tertiary treatment is needed to provide additional removal of contaminants such as microbial

Fig. 1



Current Opinion in Environmental Science & Health

Conventional two stage biological wastewater treatment and potential options for wastewater reuse.

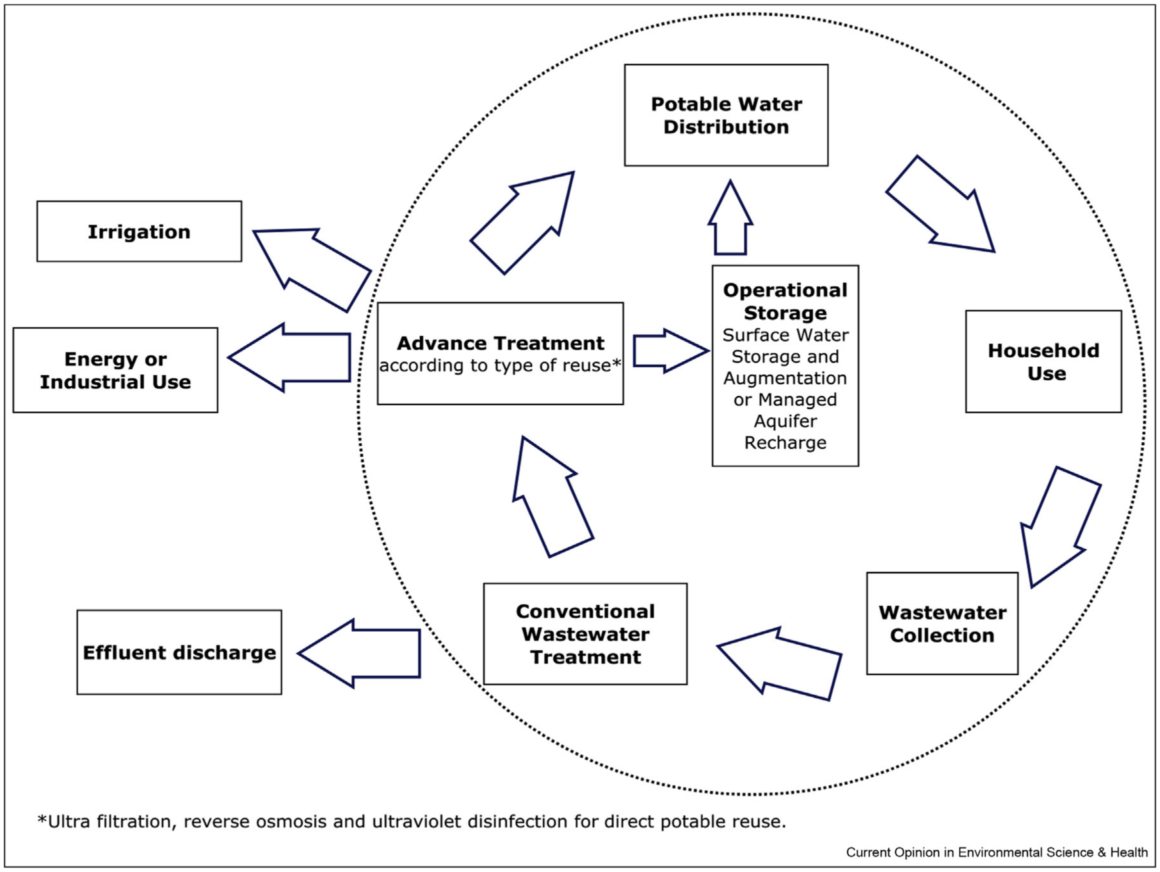
pathogens, particulates, or nutrients, and advanced treatment processes are employed when wastewater is to be reclaimed for reuse, depending on the type of use and quality requirements [49]. Pharmaceutical substances are also often detected in sewage effluents as well as receiving waters in many parts of the world [44]. Various treatment options, including engineered and managed natural treatment processes, exist that could mitigate microbial and chemical contaminants in reclaimed water, facilitating the process to meet specific water quality objectives [55]. Advanced treatment processes are capable of also addressing contemporary water quality issues related even to potable reuse involving emerging pathogens or trace organic chemicals [55]. Overall, reusing water requires physical and chemical treatment processes, pipelines, waste disposal mechanisms, and other systems [77]. The level of treatment will depend on the water quality needed for the proposed use (Fig. 2).

Water reuse as an emerging solution

Many cities are running out of options, and they are realising that high grade urban water reuse is much cheaper than the alternatives [56]. Although it is water scarcity and water supply demands in arid and semi-arid regions that have driven reuse as an alternate water supply; there are still many water reuse programmes, for example in the US, that have been initiated in response to rigorous and costly requirements to remove nutrients (mainly nitrogen and phosphorus) from effluent discharge to surface waters that could potentially also include emerging contaminants and micropollutants, when the receiving waters are intended for potable use [68]. Environmental concerns over negative impacts from increasing nutrient discharges to coastal waters are resulting in mandatory reductions in the number of ocean discharges in Florida and California in the US but also numerous sites in the UK and Europe as well [13]. By eliminating effluent discharges for all or even a portion of the year through water reuse, a municipality or a water company may be able to avoid or reduce the need for costly nutrient removal treatment processes or maintain wasteload allocations (consents on effluent discharges) while expanding capacity [22].

Treated wastewater provides an alternative source of water, particularly in areas where water is scarce. From irrigation to industrial uses to potable supply, wastewater treated to the right quality can replenish water supplies and reduce the demand/availability gap [41]. In Europe (Fig. 3), the practice of using wastewater for irrigating crops is growing and is particularly well established in Mediterranean countries such as Spain, Italy, Cyprus and Greece [5,51]. For islands and coastal regions, water recycling allows extended and thus more efficient use of freshwater by avoiding discharge to the sea. The contribution of water recycling to meeting agricultural water demand can be substantial [29]. In Gran Canaria, for example, 20 per cent of water used across all sectors is supplied from treated wastewater, including the irrigation of 5000 ha of tomatoes and

Fig. 2



*Ultra filtration, reverse osmosis and ultraviolet disinfection for direct potable reuse.

Flows of water (closing the loop) with potential applications of direct and indirect water reuse.

2500 ha of banana plantations [51]. In Cyprus, the reuse targets for 2014 equate to about 28 per cent of the agricultural water demand in 2008 [29,78].

However, in the UK, only 0.16 per cent of the 335,191,033 m^3 of wastewater treated each year is reused (in industry and for golf course irrigation). Considering that 22 billion m^3 of water is abstracted each year, 52 per cent from rivers and lakes, 11 per cent from groundwater and about 37 per cent from tidal waters (mainly used for cooling) [18], the potential of water reuse has been largely unexplored.

The transition to a circular economy

The circular economy offers a new way of looking at the relationships between markets, customers and natural resources, promoting sustainable and resource-efficient policies and practices. A business model that enables the economy to grow, while minimising the amount of virgin resources that are extracted. As many states and corporations are moving away from linear towards circular models of production and consumption, there is ample evidence that shows the need for policy and regulations to enable this, to help economies break away from a polluting economic trajectory and move to a ‘clean’ one. A transition to a circular economy will encourage a more-efficient use of water, combined with robust incentives for innovation, can enhance an economy’s ability to handle the demands of the growing imbalance between water supply and demand [47]. Although water reuse faces numerous barriers, ranging from public perception to pricing and technological, safety and regulatory challenges [83], geographical and sector-wide strategies that underpin the circular economy are emerging, and have the potential to transform some of the main barriers to water reuse.

Technical considerations

Microfiltration followed by reverse osmosis are the two principal technologies normally employed for the potable reuse of wastewater [16]. The two principal issues associated with direct potable reuse are pathogens and residual organic constituents that pass through conventional and advanced wastewater treatment systems and

Fig. 3

Current Opinion in Environmental Science & Health

Examples of water reuse programmes around the World.

are of potential health concern [54]. The most important concerns stem from the presence of priority pollutants, endocrine disrupting compounds, pharmaceutically active compounds, or other unregulated trace pollutants [60]. Residual organic compounds in reclaimed water originate from anthropogenic organic compounds added by consumers, natural organic matter already present in drinking water, and soluble microbial products generated during the wastewater treatment process due to the decomposition of organic material [42]. Advanced membrane treatments are able to achieve low total organic carbon concentrations in their product water prior to often dilution with native groundwater [55]. The most rapid growth in global water use is in manufacturing. While many industries are still mismanaging water and waste, others have become showcases of a circular economy with promising advances in good water stewardship in the manufacturing chain (e.g. 'from field to fashion' in the textile industry), not least among small-to-medium size enterprises (SME's). Some industries have demonstrated the ability to recycle and reuse water to achieve zero net water consumption, while others are striving to demonstrate a zero-pollution record [65].

Economic considerations

From a circular economy perspective, water reuse is a win–win option. The full cycle of wastewater management is a critical component of the cycle from source through distribution, collection (sewered and onsite sanitation systems) and treatment to disposal and reuse (Fig. 2), including water, nutrients and energy recovery [65]. Circular economy initiatives aim at closing resource loops and extending the lifespan of resources and materials through longer use, reuse and remanufacturing [6]. Resource recycling and reuse can help close the resources loop, providing a sustainable alternative to extracting virgin resources. However, if resources are cheap, the incentive to run a throw-away society is higher, with no reason for such synergies to take place.

Water is often free, although increasingly abstraction charges signal the scarcity value of water, reflecting its potential benefits to different users and for different purposes, and the opportunity cost entailed in using it for one purpose (e.g. agriculture) rather than for something else (e.g. urban or hydropower generation). The charge rates can be different between surface and ground water users (e.g. if local rivers were very low, or aquifers falling rapidly), but often apply to both since these two resources are inter-dependent and should be managed in a unified way [80]. Charges also vary by season, depending on the availability of water. The level of abstraction charges depends on hydrological estimates, demand projections, alternative uses, the cost of developing alternative water sources, etc. [30]. The important principle is to confront abstractors with a cost associated with their water use, which is large enough to figure in their calculations, and which is a factor in their decisions [35].

Whether water reuse makes sense for a region depends, in part, on its cost compared with the costs of other feasible water management alternatives (e.g. new supplies, expanded conservation efforts) and the cost of not pursuing any water management changes [55]. With a wide variety of treatment processes potentially incorporated into a reuse system to meet specific water quality goals for intended uses and to address local site-specific constraints, it is difficult to make general statements about the cost of water reuse. Whether reclaimed water is used for non-potable or potable uses, there are several factors that affect the costs of a water reuse program [20]. These include the location of a reclaimed water source (i.e., the wastewater treatment facility), treatment infrastructure, plant influent water quality, customer use requirements, transmission and pumping, timing and storage needs, energy requirements, concentrate disposal, permitting, and financing costs [55].

Social considerations

Non-potable and potable (principally in-direct potable) water reuse initiatives in the United States have faced increasing public opposition. Several high-profile initiatives have been halted after several years of planning and significant expenditure. Five principles have emerged from the learning process [37]: 1. Manage information for all; 2. Maintain individual motivation and demonstrate organizational commitment; 3. Promote communication and public dialog; 4. Ensure fair and sound decision making and decisions; 5. Build and maintain trust.

The public are becoming more environmentally concerned, and as a result recycling water is increasingly perceived as natural as any other recycling, and more environmentally friendly than big dams, diverted rivers, and desalination. Public perception comes down to how much people trust governments to make sure their drinking water is safe [43]. People need to understand where water comes from, and all the things that already ultimately get filtered out. The Singaporean government (Fig. 3) had a publicity campaign for the NEWater scheme. There was community concern that it would mean 'drinking toilet water'. In the end, in Singapore, they didn't wait to win over the public — they just did it. However, when NEWater entered potable supply, it only represented 1 per cent of total daily water consumption (11.4 million litres per day) rising to less than 2.5 per cent today, with the majority of it for non-potable applications [59]. Furthermore a few studies have also demonstrated that the real barrier to water reuse is often not public perception but the authorities' perception of public perception [15].

Water quality risks

The potential promotion of water reuse from a circular economy perspective could also pose some significant risks, in particular with regards to water quality and human health. There are many concerns and unknowns about the impact of the quality of the recycled water depending on its use. For example, water quality issues can create real or perceived problems in agriculture including nutrient and sodium concentrations, heavy metals [9], and the presence of contaminants such as human and animal pathogens, pharmaceuticals [45] and endocrine disruptors [50], when irrigating with water reused [69]. Social attitudes to the use of crops that have been irrigated with recycled waters and the resulting impact on market value of crops are also a major consideration [69].

A review of existing reuse schemes and regulations on the level of treatment required (Table 1) and allowable levels for contaminants in reclaimed water across the world (Table 2) found considerable variation. Most regulations are limited around the necessary water quality for different end uses, with some regulations written years ago and now need to be updated in order to reflect the current water crisis, while also considering the technologies of today.

Reuse systems, particularly in potable applications, should include a multi-barrier treatment framework composed of advanced unit processes, and they should incorporate resiliency (i.e., ability to adjust to upsets), redundancy (i.e., backup systems), and robustness (i.e., features that simultaneously address multiple contaminants) in order to succeed [55]. Recycling and reuse offer a strategy to improve water supply by managing wastewater better and while in a circular economy context they could be promoted through policy instruments such as charges and tariffs, increasing their cost effectiveness and acceptability, care must be taken with addressing real and perceived water quality issues [52]. The overall viability of water reuse is a vital consideration in the transition to a circular economy.

Discussion

The 'circular economy,' a term perhaps unfamiliar just a few years ago, is taking shape as a viable, practical alternative to the current linear economic model [81]. It refers to an economy's ability to grow while resource use is declining; the decoupling of economic growth from resource consumption and pollution. The business case for a transition to a circular economy is compelling both in terms of economic outputs and jobs, and although this creates the right conditions for the widespread application of water reuse, water quality issues real or perceived remain the main barriers to this.

In Europe, over abstraction of water from surface and groundwater bodies is a significant pressure in some areas, while in most densely populated areas, the water abstracted is purified, used by people or industry and then collected and treated at a municipal wastewater treatment plant before discharged (as effluent) back into a river, only to be abstracted a second (or subsequent) time further downstream [63]. The water sector continues to face challenges relating to water quality and the reduction of chemical pollutants, which can poison aquatic organisms, accumulate in the ecosystem, damage habitats and threaten human health. As a result, installing advanced (and expensive) treatment technologies at sewage treatment works may be necessary. For example, water companies are striving to reduce the levels of nitrates and pesticides such as metaldehyde in the water that are often the result of run-off from farmland, through catchment initiatives with farmers or advanced treatment of water for potable use. For example, over 12.5 million people live within the catchment of the River Thames in southern England, each using approximately 200 L of water per day producing wastewater collected and treated by 352 wastewater treatment plants, all of which discharge their effluents into the main body of the river, or its tributaries [79]. The flow of some of these tributaries (if they have major treatment works on them) can consist primarily of effluent—a value of over 90 per cent is reached for some stretches in times of low or no rainfall, and even the main river is effluent dominated [67]. It is in these areas, that the presence of "contaminants of emerging concern," a broad category of water pollutants – such as pharmaceuticals and chemicals – that are not removed by traditional wastewater treatment, will soon require advance treatment to remove these from wastewater, making the case for direct potable reuse, in comparison, viable [36]. The introduction of environmental regulations that require effluent quality delivered by advanced wastewater systems that remove emerging contaminants such as EDCs and other organic micropollutants would make direct water reuse more profitable in comparison to discharging the effluent to a lower quality receiving water body only to abstract and clean again later [73]. In addition, in terms of public perception, the case could be made that it is better to reuse directly and treat water with advance methods, rather than continue with indirect reuse, but where the water is not treated to the same quality [61]. Similar could be the case for 'indirect reuse', occurring when wastewater gets diluted but still remains a dominant component of surface water flows used for irrigation [70].

In comparison to conventional source waters, potable reuse is often scrutinized more carefully by the water industry, held to higher water quality standards by water regulators, and tested for a wider range of chemical and microbial contaminants. Despite an inevitably higher level of initial contamination, these systems may provide a greater level of public health protection than many of the water sources treated with conventional drinking water processes supplying our tap water today [55].

Water reuse offers the potential to transform the linear human water cycle (abstract, treat, distribute, consume, collect, treat and dispose) into a circular flow by closing the loop, but also potentially decoupling municipal water consumption from the depletion and pollution of water reserves [73,75]. Its role in addressing water resources problems needs careful investigation and the consideration of technical, economic, social, environmental and also legal aspects through a coherent analytical framework [64]. For example, treating wastewater for reuse (diverted from wastewater treatment plant discharge) may have an impact on river flow levels, which could affect both the ecology and water availability for

Table1

Types of treatments for reclaimed water as regulated by various international authorities.

Use of water	Regulators/Guideline providers							
	USA (EPA)[a]	Australian guidelines for water recycling[b]	EU Guidelines[c]	Mediterranean (UNEP)[d]	California[a]	Nevada[a]	Washington[a]	WHO Guidelines[e]
Direct contact with food or food contact surfaces or the public	Food crops eaten raw and not processed: Secondary treatment (sludge treatment, trickling filters, rotating biological contractors) Filtration (pass through soils) Disinfection (UV, ozonation, chemical etc.) Food crops commercially processed: Secondary Disinfection Urban reuse with public exposure: Secondary filtration disinfection	**Household use (non-potable)** Secondary treatment Coagulation Filtration Disinfection Membrane filtration UV light **Municipal use (watering public spaces)** Secondary treatment Coagulation Filtration Disinfection Membrane filtration UV light **Food crops eaten raw:** Advanced treatment to achieve total pathogen removal required (eg secondary, filtration and disinfection) **Food crops that do not come into contact with water or have a skin** Secondary treatment with >25 days lagoon detention and disinfection	Class A: food consumed raw Secondary treatment, filtration, and disinfection (advanced water treatments) Class B: food consumed raw without skin Secondary treatment, and disinfection Class C: food consumed raw without skin watered straight into the ground Secondary treatment, and disinfection	Category I* Secondary treatment+ filtration+ Disinfection Category II** Secondary treatment or equivalent+ filtration+ disinfection or Secondary treatment or Equivalent+either storage or well-designed series of maturation ponds or infiltration percolation	Non restricted recreational impoundments: • Secondary • Coagulation • Clarification • Filtration • Disinfection Food crops and urban use: • Secondary • Coagulation • Filtration • Disinfection	Restricted urban reuse: Secondary treatment Disinfection Agricultural reuse (food crops): Secondary treatment Disinfection	Restricted urban reuse: Oxidised Disinfected Agricultural reuse (food crops): Oxidised Coagulated Filtered Disinfected	**Concerns use in agriculture:** - General: - Wastewater treatment - Health and hygiene promotion - Excreta treatment - Chemotherapy and immunisation **Consumers of food: produce restriction** - Waste application/ timing - Depuration - Food handling and preparation - Produce washing/ disinfection - Cooking foods **Workers and local communities:** - Access control - Use of personal protective equipment - Disease vector control - Intermediate host control - Access to safe drinking water - Reducing vector contact (nets etc.)

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Table1. (*continued*)

Use of water	Regulators/Guideline providers							
	USA (EPA)[a]	Australian guidelines for water recycling[b]	EU Guidelines[c]	Mediterranean (UNEP)[d]	California[a]	Nevada[a]	Washington[a]	WHO Guidelines[e]
No direct contact with food or food contact surfaces	Non-food crops: Secondary disinfection	Municipal use (restricted public access) Secondary treatment Disinfection	Class D: non-food crops: Secondary treatment, and storage, stabilization ponds or constructed wetlands.	Category III*** Secondary treatment or equivalent+a few days storage or Oxidation pond systems Category IV**** Pretreatment as required by the irrigation technology, but not less than primary sedimentation	Food crops (no contact with edible portion) fish hatcheries, restricted recreational use: • Secondary • Disinfection Pasture, cleaning roads, non-food crops: Coliform limits: • Secondary • Disinfection Irrigation of fodder, fibre and seed crops or where irrigation is straight into the ground • Secondary	Agricultural reuse (non- food crops): Secondary treatment Disinfection	Agricultural reuse (food crops): Oxidised Disinfected Industrial reuse: Oxidised Disinfected	Correctly label all other water depending on whether it is grey water, waste water, reclaimed water, green water or drinking water.

*Direct contact with the public likely.

**Direct contact with food crops.

***Irrigation but not direct contact with food.

****Direct to floor irrigation.

[a] U.S. EPA [74].

[b] NRMMC [57].

[c] Alcalde Sanz etal. [2].

[d] Bahri and Brissaud [3].

[e] WHO [82].

Table 2

Allowable levels for contaminants in reclaimed water as regulated by various international authorities.

Use of water	Guideline provider/regulator								
	Mediterranean[a]	Australia[b]	USA – EPA[c]	EU Guidelines[d]	Nevada[c]	Texas[c]	Washington[c]	California[c]	WHO Guidelines[e]
Direct contact with the public and food	Category I* Intestinal nematode ≤0.1 eggs per litre – fortnightly Faecal Coliforms or *Escherichia coli* ≤200 colony forming units/100 ml – twice weekly Physical/Chemical suspended solids ≤10 mg/L – weekly	*E. coli* Not detected in 100 Ml Monitored weekly Turbidity <1 NTU (95%) <5 NTU (max) Monitored continuously online pH 6.5–8.5 Monitored continuously online Disinfection Chlorine: 0.2–2.0 mg/L residual Monitored continuously online	**Food crops eaten raw and not processed:** - pH – 6–9 test weekly - BOD – ≤10 mg/l test weekly - Turbidity – ≤2 NTU test continuous - Coliform – No detectable test daily - CL_2 residual – 1 mg/L residual minimum test continuous - Set back 15 m from potable water wells **Food crops commercially processed:** - pH – 6–9 weekly - BOD – ≤30 mg/l test weekly - TSS – ≤30 mg/l test daily - Coliform – <200 faecal coliform/100 ml test daily - Cl_2 residual – 1 mg/L residual minimum test continuous - 90 m from potable supply wells - 30 m from public access if spray irrigation	Class A: food consumed raw *E. coli* – ≤10 colony forming units/100 ml Test once a week BOD – ≤10 mg/l Test once a week TSS – ≤10 mg/l Test once a week Turbidity – ≤5NTU Test daily	Agricultural reuse (food crops): BOD: 30 mg/L 400 faecal coliform/100 ml (max)	Agricultural reuse (food crops): BOD: 5 mg/L 75 faecal coliform/100 ml (max)	Agricultural reuse (food crops): BOD: 30 mg/L 23 total coliform/100 ml (max)	Non restricted recreational impoundments and food crops and urban use: coliform limits: ≤2.2/100 mL ≤23/100 mL in more than one sample in any 30-day period 240/100 mL	Unrestricted irrigation *E. coli* per 100 ml Root crops ≤1000 Leaf crops ≤10,000 Drip irrigation, high-growing crops ≤100,000 ≤1 helminth eggs per litre
Indirect contact with food and restricted public access	Category II** Intestinal nematode ≤0.1 eggs per litre – fortnightly Faecal Coliforms or *E. coli* ≤1000 colony forming units/100 ml – weekly	–	Urban reuse with public exposure: pH – 6–9 test weekly BOD – ≤10 mg/l test weekly Turbidity – ≤2 NTU test continuous Coliform – No detectable test daily	Class B: food consumed raw without skin *E. coli* – ≤100 colony forming units/100 ml Test once a week BOD – ≤25 mg/l Test once a month	–	–	–	Food crops (no contact with edible portion) fish hatcheries, restricted recreational use: coliform limits: ≤2.2/100 mL ≤23/100 mL in more	Restricted irrigation Labour-intensive, high-contact agriculture *E. coli* per 100 ml ≤10,000 Highly mechanized agriculture ≤100,000

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Table 2. (*continued*)

Use of water	Guideline provider/regulator								
	Mediterranean[a]	Australia[b]	USA – EPA[c]	EU Guidelines[d]	Nevada[c]	Texas[c]	Washington[c]	California[c]	WHO Guidelines[e]
	Physical/Chemical suspended solids ≤20 mg/L (≤150 mg/L for stabilisation ponds) - weekly		CL_2 residual – 1 mg/L residual minimum test continuous Set back 15 m from potable water wells	TSS – ≤35 mg/l Test once a month Turbidity – Do not test				than one sample in any 30-day period	≤1 helminth eggs per litre
Agricultural and urban use, lower contact with food and the public	Category III*** Intestinal nematode ≤1 eggs per litre – monthly Faecal Coliforms or *E. coli* No test required – twice monthly Physical/Chemical suspended solids ≤35 mg/L (≤150 mg/L for stabilisation ponds) - monthly	*E. coli* <10 cfu/100 mL Monitored monthly Turbidity <5 NTU (95%) Monitored continuously online pH 6.5–8.5 Monitored continuously online Disinfection Chlorine: 0.2–2.0 mg/L residual Monitored continuously online	Urban reuse (toilets, landscaping, vehicle washing): pH 6–9 (test weekly) ≤10 mg/L biochemical oxygen demand (BOD) (test weekly) ≤2 Turbidity units (NTU) (continuous testing) No detectable faecal coliform/100 mL (test daily) 1 mg/L Chlorine residual minimum (continuous testing)	Class C: food consumed raw without skin watered straight into the ground *E. coli* - ≤1000 colony forming units/100 ml Test once a week BOD – ≤25 mg/l Test once a month TSS – ≤35 mg/l Test once a month Turbidity – Do not test	Restricted urban reuse: BOD: 30 mg/L 240 faecal coliform/ 100 ml (max)	Restricted urban reuse: BOD: 20 mg/L 800 faecal coliform/ 100 ml (max)	Restricted urban reuse: BOD: 30 mg/L 240 total coliform/ 100 ml (max)	Pasture, cleaning roads, non-food crops: Coliform limits: • ≤23/100 mL • ≤240/100 mL in more than one sample in any 30-day period	–
No contact with food or the public (possible use in irrigation with direct to floor methods)	Category IV**** Does not require testing	–	Non-food crops and pasture: pH 6–9 (test weekly) ≤30 mg/L BOD (test weekly) ≤30 mg/L total suspended solids (test daily) 200 faecal coliform/ 100 mL (test daily) 1 mg/L Chlorine residual minimum (continuous testing)	Class D: non-food crops: *E. coli* - ≤10,000 colony forming units/100 ml Test once a week BOD – ≤25 mg/l Do not test TSS – ≤35 mg/l Do not test Turbidity – Do not test	Agricultural reuse (non- food crops): BOD: 30 mg/L 400 faecal coliform/ 100 ml (max)	Industrial reuse: BOD: 20 mg/L 800 faecal coliform/ 100 ml (max)	Industrial reuse: 240 faecal coliform/ 100 ml (max)	No limits for fodder, fibre and seed crops or where irrigation is straight into the ground	–

*Direct contact with the public likely

**Direct contact with food crops

***Irrigation but not direct contact with food.

****Direct to floor irrigation.

[a] Bahri and Brissaud [3].

[b] NRMMC [57].

[c] U.S. EPA [74].

[d] Alcalde Sanz et al. [2].

[e] WHO [82].

downstream abstraction. The impact, if any, of a water reuse scheme would be specific to the individual project. Therefore, the impact of the reuse scheme on the local hydrological regime (and therefore on the environment and dependent users) should be assessed on a case-by-case basis in advance of project development. Taking ecosystem services into account and valuing them properly [76], could further facilitate this.

One of the key aspects of planning and designing a water reuse scheme is the quality (and the variation in the quality) of the influent wastewater (secondary effluents), the quality requirements of the purpose of use and reliability of operation. Design and implementation of an under-performing treatment system could lead to unacceptable or unreliable water quality for water reuse purposes (defeating the object of improved resilience and water security). For example, appropriate treatment selection should be based on the best available technology, standards, legislation and sound knowledge, keeping in mind that even an advanced treatment could pose a higher risk than the use of treated wastewater with a lower treatment (e.g. discharge of disinfection by-products such as trihalomethanes). In any case, planning and designing a water reuse scheme should be informed by risk assessment, to identify the potential benefits and any potential drawbacks and so help make better decisions on whether to introduce that scheme and, if so, help improve its design. It is also important to note that many benefits and risks will be specific to local circumstances and, therefore, need to be determined on a case by case basis.

Conclusion

Addressing humanity's ever-increasing demand for resources, water, energy and food, will require a combination of approaches including water conservation, recycling, and treatment of impaired water from non-traditional resources to "create" new water [39]. Recycling and reuse are central to a circular economy approach and offer a strategy to improve water supply by managing wastewater better. Water reuse faces numerous barriers, ranging from public perception to pricing and regulatory challenges that could be addressed more effectively though a wider circular economy perspective. An integrated, interdisciplinary and holistic approach would facilitate the application of water reuse as part of an integrated water management strategy that could be significantly accelerated in the context of a circular economy. Such strategy should also ensure the safety of water reuse, and therefore apply water quality standards appropriate to the specific use, but also ensure adequate and reliable operation of water reuse systems and appropriate regulatory enforcement.

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