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SHORT COMMUNICATION

Circular Economy of Water: Definition, Strategies and Challenges

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Abstract

The circular economy has attracted considerable attention also in relation to water, an indispensable element to the sustainment of life and a critical input resource for the world economy. Despite a growing body of research on the circular economy of water (CEW), a consistent terminology and a clear conceptualisation of CEW strategies are lacking. Without such aspects, decision-makers, scientists and professionals may be hindered in developing a shared understanding of problems and solutions and exploiting new opportunities in the domain of the CEW. Furthermore, we argue that water is a unique element in the circular economy because it is a resource, a product and a service with no equivalent in the economic system and should be considered and valued as such in the CEW. Accordingly, we provide the definition of the CEW as an economic framework for reducing, preserving and optimising the use of water through waste avoidance, efficient utilisation and quality retention while ensuring environmental protection and conservation. Building on an analysis of academic literature and cases studies, we outline and illustrate a set of nine CEW strategies, including Rethink, Avoid, Reduce, Replace, Reuse, Recycle, Cascade, Store and Recover. Finally, we identify normative (legislation), governance (roles and responsibilities) and implementation (barriers and opportunities for application) challenges that need to be addressed to facilitate the transition to a comprehensive CEW.

Keywords Circular economy of water · Strategies · Definitions · Water system · Sustainable water management · Water governance

Introduction

Water is an essential natural resource and is used for economic purposes as a critical input for agriculture, industry, electricity generation and urban and recreational activities [1, 2]. Over the years, these resource-intensive activities and global environmental change have increasingly affected water quality and availability worldwide. Furthermore, population growth,

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economic development and changing consumption patterns have dramatically increased water demand, resulting in mounting tensions over water supply [3–5]. As such, a key challenge in today's world is to ensure enough water for use across all sectors, while respecting environmental flows, and doing so sustainably [6–8]. With the latest scientific and technological advancements in the water sector, academics, governments, water utilities and industry have been considering more efficient models for managing water [9–11]. The circular economy (CE) has been proposed as an effective framework for sustainable water management (e.g. [12–14]). After all, principles such as a closed loop supply chain, value retention, waste minimisation and resource efficiency lend themselves well to the water sector. Furthermore, the CE is well suited to support the management of water supply, as like water, intersects with multiple spatial scales (from super-local to global), levels of governance (micro, meso and macro), forms of implementation (from design to post-use) and economic sectors. Finally, the CE can also be applied to different water uses (e.g. irrigation, sanitation) and water-management flows (e.g. water saving, harvesting). The CE applied to water also represents ways to achieve the Sustainable Development Goals (SDG) specifically SDGs 6 'Clean Water and Sanitation', 9 'Industry, Innovation and Infrastructure' and 12 'Responsible Consumption and Production'. More indirectly, it could help to achieve practically all other SDGs.

In recent years, scholars have introduced expressions such as 'circular economy of water', 'circular water economy' or 'water circular economy' (e.g. [14–18]); however, none of these have yet solidified in the discipline as key terminology. In parallel, many published works speak about 'CE and water', while others do not mention the CE although dealing with its principles. In this paper, we will adopt the term 'circular economy of water' (CEW).

Despite the growing interest in the CEW, broader research efforts remain sparse. In our view, there is a need for a nuanced conceptualisation in which water is considered as a special case in the CE because it is a resource, a product and a service, with no equivalent in the economic system. Accordingly in the 'The Uniqueness of Water and a Definition of the CEW' section, we clarify the concept of CEW and propose a specific definition. In addition, awareness must be raised on the range and scope of CEW strategies. Reuse and recycling currently dominate the debate about the CEW, and the CE terminology is oftentimes employed inaccurately. For these reasons, in the 'Strategies for the Circular Economy of Water' section, we propose a clear-cut and comprehensive set of strategies for managing water that can capture the entirety of CEW. These strategies are derived from an analysis of the academic literature and the knowledge base of KWR Water Research Institute (KWR), an internationally recognised institute for excellence in water research.

A specific definition of the CEW and a wider set of strategies could strengthen the conceptualisation of the CEW while helping decision-makers, scientists and professionals developing a shared understanding of problems and solutions and exploiting new opportunities in the domain of the CEW. By developing consistent terminology and a clear focus on strategies relating to the CEW, this study aims to integrate past and future studies and facilitate the transition towards sustainable water management. A full understanding of the CE proposition could also prove to be timely and necessary in terms of rethinking how water is used and to build a strong vision for the years to come.

The Uniqueness of Water and a Definition of the CEW

Water is a distinctive element in the CE: it is available both as a stock and a flow. It is a substance that exists in different states (liquid, solid and gaseous); it can be variably saline and contains different quantities of chemical elements. Water is also found in a range of forms and locations (such as groundwater, brackish water and superheated water). Finally, water has several natural entry points (including rivers and aquifers), and it follows numerous streams in human and natural systems [1, 19, 20]. These varied forms demonstrate that water is unique and underline the difficulty of adopting a single approach to it in the CE.

Water can be a resource, product or service depending on the context: it is indispensable to the sustainment of life and is the critical input resource for the world economy (industrial processes, service delivery and food and energy production all relate to water). Water is a product when it is sold, but it is also embedded in products (as virtual water, e.g. in all products of biological origin). Water is also a service: it is used to store or produce energy (kinetic, thermal, biothermal), as a carrier of biogenic raw materials that provides basic services for ecosystems (including the habitat) and human activities [12, 21].

The common definitions of the CE generally relate to industrial activities in the socio-economic system as a whole [22], but appear to be inadequate to capture the multifaceted aspects of water. This study therefore proposes an ad hoc definition that encompasses all of water's particularities within the CE: the CEW is an economic framework for reducing, preserving and optimising the use of water through waste avoidance, efficient utilisation and quality retention while ensuring environmental protection and conservation. In this model, water is seen as a precious resource, product and service to be managed sustainably within the natural water cycle. These aims should be met in all processes in which water is used, consumed or treated.

In any sector, the CEW offers novel opportunities for innovation, governance, business models and water management together with new views on engineering and technological solutions (e.g. [23–27]). For instance, smart network technologies can deliver unprecedented options for sustainable water management and scaling up the CEW (see, e.g. [28]). The CEW does also embrace traditional, socially innovative and nature-based solutions [29–32] as long as those solutions close loops, use water efficiently, prevent waste or maintain water quality for long periods. At the same time, there is a need to minimise the trade-offs and rebound effects of those CEW solutions that have a negative effect on environmental benefits. These effects may occur, for instance, when increased water efficiency results in higher water consumption [33, 34]. Finally, the CEW can play a key part in sustainable water management and could result in the reorganisation of water use and valorisation while redefining the roles of actors and governance actions. CEW solutions could therefore be key to several transitions (e.g. energy, agri-food systems, sustainable consumption/production) and an effective framework to address the challenges of global environmental change.

Strategies for the Circular Economy of Water

A set of clear strategies represent a crucial level of analysis for the CEW. Strategies are approaches adopted by organisations in order to attain their objectives while guiding change and transition [35]. CEW strategies are therefore the main pathways leading to more circular use of water and constitute the categories to which the various CEW solutions and applications can be traced back. CEW strategies therefore act as reference points for all actors using different types of water. When taken together, strategies provide an integrated view of CEW and of the possible means to implementation.

Several studies have identified CE strategies. The most common in the CE literature include Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover (known as the R-strategies) [35, 36]; however, some of these strategies refer to general resources and types of industrial production that do not fit the water context. For example, Repair, Refurbish and Remanufacture are strategies for manufactured products, while Repurpose refers to the use of discarded products to make new ones. Strategies in the CE literature also include waste-to-energy solutions (e.g. waste incineration) which cannot be applied to water. This study therefore provides a critical evaluation of the CE strategies in the literature vis-à-vis the extant research on water management and reflects on their relevance and applicability to water, and — ultimately — on the need for additional strategies that specifically address water. For the purposes of the analysis, we reviewed scientific articles discussing circular economy and water and related strategies from Scopus and Web of Science databases that used the words 'water', 'strategies' and 'circular economy' up to 2020. However, the words 'water' and 'strategies' can be used in articles not specifically discussing water or CE strategies; for this, the preliminary results needed to do be distilled through an attentive reading of the text to eliminate the items not in line with the research objectives. The search resulted in a collection of 50 relevant studies. We also identified 26 extra publications using the snowball method (see Annex for all the results).

These articles were complemented with circular water solutions taken from 22 cases, 10 from Nextgen, a European-funded research project, and 11 from Water in the Circular Economy (WiCE), a research programme of the Dutch and Flemish water utilities and KWR, with partners from the water authorities, regional and local governments, industry and academia. The possibility of adding additional CE strategies was considered based on the verification of case studies and discussions with several experts and practitioners in the sector.

Our analysis showed that some of the CE strategies, namely Reuse, Recycle, Rethink, Reduce and Refuse/Avoid, need to be re-calibrated for water. These strategies were supplemented by others such as Replace and Store that are specific to water or that re-interpreted existing strategies such as Recover or Cascading [36]. The set of strategies is shown in Fig. 1.

Except for Rethink, which is considered a stand-alone and overarching strategy, the strategies have been allocated to three categories: decreasing, optimising and retaining. Before discussing each category and strategy, two important issues and one caveat should be explained in more detail.

First, Fig. 1 does not establish any hierarchy for the strategies: the same water can be used multiple times for different purposes and in different contexts. The second issue relates to the definition of the system boundaries that apply to CEW strategies. In this study, the system boundaries are those delimited by any natural or artificial system in which water is managed for economic purposes because the CE is an economic model. The CEW as a system has several entry points (including water extraction, catchment and harvesting) and exit points (e.g. leakage, evaporation and discharge). However, returning water to the global water cycle is not considered a CE strategy because water is no longer retained inside the economic system.

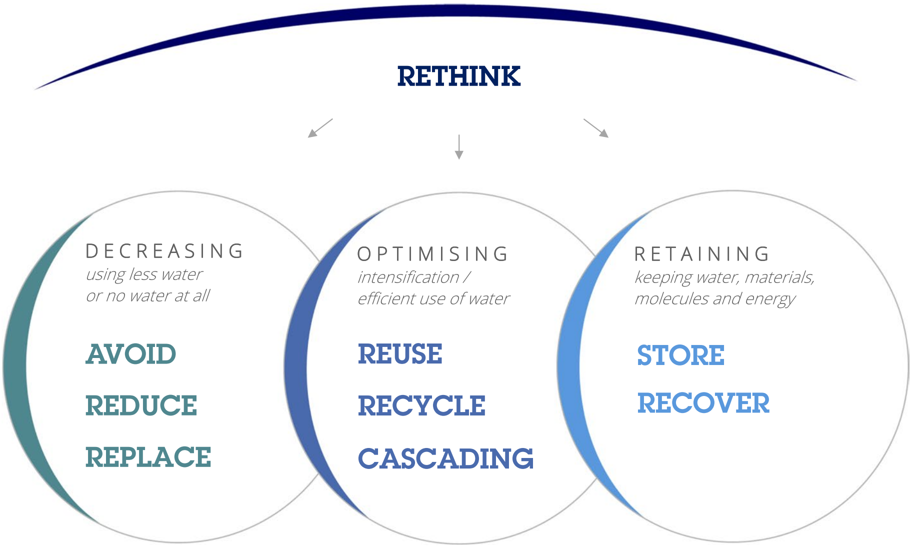


Fig. 1 strategies for the CEW

The caveat concerns factors that are not considered as strategies. By nature, water has multiple purposes, and it can always be repurposed (e.g. for cooling and then cleaning). Nevertheless, Repurpose cannot be a strategy for water because used water comes under the Reuse or Recycle category (see below). Restore, sometimes also referred to as Replenish, involves returning water used by humans to natural systems, a process that is also covered by legislation with defined parameters. Restore is a CE principle and an important action for the functioning of natural systems [37]. However, it cannot be a strategy because it exceeds the defined boundaries of the CE system. Reclamation, the application of technologies for the removal of pollutants from water/wastewater, is covered by the Recycle category (see below). Desalination (the removal of salts from water) implies processing sea water or groundwater to produce potable water, and it is categorised as water extraction.

In the remaining part of this section, we analyse each strategy providing a definition and a few meaningful examples. The purpose is not to give a comprehensive review of each strategy but support the overall understanding of each strategy and the differences among them.

Rethink

Rethink is about reconfiguring and re-conceptualising how water is used to favour a more circular utilisation. It implies the re-design/restructuring of the operative aspects of water use such as the practices, processes, policies, facilities and technologies. This transformational change implies thinking in a systemic way across multiple levels (from individual to international) to which solutions are applied [38]. Arguably, all other CEW strategies include a Rethink component because they imply a certain degree of change/reshaping of facilities and processes employing water. Overall, Rethink can be considered an overarching strategy that gives shape and content to all CEW strategies while creating synergistic links between them [35, 36]. Rethink can help to save and conserve water and to optimise water use, in all the relevant sectors. For example, water management practices can be adapted to close loops, reuse or recycle water or to reduce use, as in the case of rethinking the design of cooling water systems to improve performance and reduce water usage at the same time [39]. Rethink can also help to create synergies by applying multiple strategies to different water uses. Rethink can support the smarter design of water infrastructure to use water sources more efficiently, favouring the development of CE solutions. Finally, Rethink can help reshape legislation in favour of specific circular solutions by supporting stakeholder collaboration or integrated circular water management across multiple sectors.

Decreasing the Amount of Water Use

This category includes three strategies to use less water or no water at all: Avoid, Reduce and Replace.

Avoid

Avoid means preventing the use of water. In the literature, Avoid is rarely acknowledged as a stand-alone strategy, despite Refuse being a well-established strategy in the CE for products and other resources [35]. We opt for the term Avoid because it evokes the ideas of renouncing and preventing water use at the same time. In the few cases, Avoid is mentioned (e.g. [12]); it is mainly used to refer to either eliminating inefficient uses or reducing water use. However, this is still a reduction of water use, and it does not capture the actual meaning of Avoid.

Here, we interpret Avoid as an extreme form of Reduce, in other words as a 100% reduction of water use. By contrast with Reduce, where the goal is to use less water than before, Avoid implies not using water at all. In practice, Avoid is rarely applicable because it is usually difficult to stop using water. Nevertheless, there are several examples of water-free solutions such as water-free toilets based on vacuum flush, vacuum pumps in industry, dry wash sprays or atmospheric-plasma technologies for clothing [40–43].

Reduce

Reduce is often interpreted intuitively. In the studies that do provide definitions, Reduce means (a) using less water [44], (b) extracting less water from the source [45] and (c) using water efficiently [12, 15]. The first definition seems to be the more accurate of the three. The second definition is a consequence of reducing water use, while the third is a way to reduce water use. Reduce therefore means using less water than in the business-as-usual scenario. This strategy can be applied across sectors, for example, in domestic consumption with wellness showers combining water and air bubbles or water-saving dishwashers; in the agricultural sector, it can be applied by using precise irrigation or crops requiring less water or in the industrial sector by using processes that demand less water such as solar water heating processes that do not require steam. Other examples of Reduce include applying biochar to improve water retention of soil [46] or using tile drainage system for water management [47]. Reduce has probably been the most successfully applied strategy in recent years due to favourable pricing and awareness campaigns. In principle, water's necessity means that Reduce cannot be applied indefinitely. There are biological and physical limits to the extent of the reduction of water consumption. Living organisms, wastewater treatment and industrial processes need minimum amounts of water to function.

However, innovation in processes and technologies can support the continuous development of Reduce solutions [48].

Replace

Replace is scarcely mentioned in the CE and water literature. Replace is similar to Avoid because both imply renouncing water. However, by contrast with Avoid, Replace substitutes water with another substance. Examples include the use of foam or compost toilets in households and replacing water with heat transfer fluids such as synthetic hydrocarbons (dielectric fluids, for example) in industrial processes [49–51]. To remain truly circular, the materials used to replace water should also comply with CE thinking and should not harm the environment. A variation of Replace could be the substitution of high-quality water with lower-quality water, for instance, using greywater for irrigation, cleaning or flushing operations [52]. Like Avoid, Replace is not an easy strategy to implement because water is a relatively cheap resource with unique physicochemical and biochemical properties. Furthermore, water is easily available due to a large network of infrastructures that have been built and maintained over a long time. All these factors make it economically and physically challenging to replace water with other substances. Nevertheless, both Avoid and Replace are important strategies in terms of encouraging the development of innovative solutions that could prove crucial in water-scarce regions.

Optimising the Use of Water

This category refers to the strategies devised to use water more efficiently or intensively than before. In this case, savings derive from using the same water more than once.

Reuse

Reuse and Recycle are often used interchangeably in the literature. This ambiguity derives from the semantic similarity of the two words and the lack of standard definitions. However, this study suggests that a distinction is possible and advisable.

This study proposes defining Reuse as using water again for the same or another purpose without any treatment. In this definition, in line with other authors (e.g. [27]), treatment is what differentiates Recycle from Reuse. Treatment involves actions and costs. Reuse is associated with the notion of no-treatment-needed for the subsequent use of water. This interpretation fits in with the meaning of Reuse for products in common CE practices where, for example, the same object (such as a rental tool) is reused by different people. Despite the fact that legislation has often come to refer to the repeat use of water after treatment as Reuse [53], conceptualising the CEW offers the opportunity to improve and standardise definitions.

Although the Reuse/Recycle distinction is feasible, it should be noted that Reuse practices are rare when dealing with water. Without treatment — meaning that not even a drop of any substance (such as chlorine) is used to change the water quality — the biological stability of water is limited in time, and further use can be jeopardised. Water is therefore often reused immediately after the first use, which implies that subsequent use will be located nearby. When reused, water can have the same quality/value as in previous uses or — and this is more frequently the case — the quality may not be as high (this is therefore a case of the downcycling of water). In the CE lexicon, downcycling and its opposite, upcycling, refer to recycled materials (examples being glass or plastic). However, in the case of water, the terms can also refer to Reuse. In general, Reuse requires levels of previous contamination/alterations to be acceptable and not to interfere with further uses [13, 54]. Reuse is therefore most applicable in the same production cycle (inner loop) or in a nearby/contiguous production process. For instance, water for cooling or water from operations can be reused in the same industrial processes or in industrial activities nearby [55, 56].

Recycle

Recycle is using water again after treatment for the same or other purposes. There are many treatment techniques and technologies, and they vary depending on the intended Recycle purpose. As in the case of other recycled materials (such as paper or plastic), treatment makes it possible to attain the quality standards required for subsequent uses. In the case of water, particles or chemical/biological contaminants are removed, or concentrations are lowered to acceptable levels. Recycle can encompass a single treatment (e.g. debris removal) or several simultaneous or sequential chemical, physical and biological treatments, as in the case of water treatment processes (e.g. coagulation, flocculation, sedimentation [57–60]). Treatment tends to enhance water quality/value (upcycling). It is possible to recycle the same water several times, as in space technologies developed in the context of the European Space Agency's long-running MELiSSA programme [61]. Here, recycling water involves an articulated system of membranes, photobioreactors and a pool of algae and bacteria. These solutions have been applied in several contexts, such as space stations, brewery facilities or wastewater recycling from showers, washing machines and dishwashers. Furthermore, nature-based solutions (e.g. aquatic plants, constructed wetlands) can be highly effective in recycling water, aside from its other environmental benefits [62, 63]. In recent years, some industries such as the paper industry and dyeing industries have progressively adopted recycling solutions in response to water pricing and environmental regulation [64]. However, the recycling of wastewater may be counter to national legislation, and safety legislation in particular or society may find it undesirable [53, 65, 66].

Cascading

Cascading is a sequence of consecutive uses of water for different purposes. To achieve this aim, multiple solutions involving different strategies can be integrated and combined. Water (whether untreated or treated) can be used again and again in multiple stages of industrial and domestic processes. For instance, steam used for energy production can be used — as condensate — for cooling, then for cleaning, and subsequently for flushing toilets; once treated, the same water can be used for irrigation [67–70]. Cascading works best under proximity, in other words when consecutive uses are located close to one another and with technologies working in synergy [71]. Cascading combines multiple CE strategies (such as Recycle, Reuse and Recover) even in the water sector (see, e.g. [72]). It is therefore not always considered a strategy in the CE literature. However, it is the strategy that best represents water in a CE model because it reflects the multiple states of water perfectly and is based on multiple interrelated uses. In an ideal CE world, water is cascaded infinitely, as in the natural water cycle of the Earth system.

Retaining Water

This category refers to strategies that store water and recover water and its embedded resources so that they are retained in the economic system.

Store

Store is the strategy in which water, after being used, is transferred to a reservoir (cisterns or artificial basins, for example) where it will be available for future uses. To describe this strategy, this study has adopted the term ‘Store’ rather than ‘Recharge’, which is often employed outside the scope of the CE (e.g. wide-ranging ‘managed aquifer recharge’ measures [73]. ‘Store’ is also more comprehensive term than ‘water banking’, which is often used in relation to drought and/or large projects [74]. Store can be interpreted as a complementary strategy alongside Reuse, Recycle and Cascading (see above). It keeps water longer in the human-managed water system, postponing its return to the natural system, allowing other uses at different points in time. Store is distinct here from restore/replenish, which involves returning water to nature. The act of storing deliberately is designed to retain water so it can be used again, generally within given periods of time. Depending on the water receptor, water may or may not need treatment before or after storing [73]. There are many examples of the Store concept. For instance, water used in greenhouses can be stored in tanks for future use, water used for energy production can be pumped back into a storage reservoir, or water can be stored in the subsurface for heating purposes [75]. Infiltration crates or smart weirs represent promising solutions for retaining and storing water for large scale deployments (e.g. [76, 77]).

Recover

Recover refers to the retrieval of valuable materials (i.e. organic matters, chemical elements, biochemical compounds) and the retention or generation of energy. Water itself can be recovered during Recover processes. Recover is justified by necessity, innovation and economic and/or political convenience. Materials can be extracted from different water flows, but mainly from wastewater and sewage sludge. Extraction requires defined processing and technologies depending on what is being recovered, whether this be nutrients (e.g. nitrogen and phosphorus), precious metals (e.g. gold, palladium), gas (e.g. methane in food residuals — see also below) or organic material (e.g. mud and proteins) [78–80]. Recover differs from removal treatments (targeting things like toxic heavy metals, pathogens and persistent micropollutants) but can be combined. Water recovery is increasingly associated with the recovery of materials. Water is separated from the concentrated flow from which materials are extracted, and instead of being discharged, water is then recovered as a valuable by-product.

Energy recovery can be done in different ways depending on the form in which energy is available. Water can be a carrier of energy, or it can itself be a medium for energy storage/production. For instance, sludge-to-energy occurs when methane is recovered from organic residues in wastewater. Elsewhere, thermal energy can be recovered from sewers and from hot water, whether from domestic sources (e.g. showers) or large industrial facilities (e.g. exhaust hot water in steelmaking). Energy can also be regained from hydraulic machines in the form of power dissipated by — for instance — valves or hydraulic pumps. Water can be used as a source for a heat pump to obtain heat at higher temperatures, which means that water pipe networks, surface water or groundwater can be a source of energy recovery [81, 82]. One example is high temperature aquifer thermal energy storage (HY-ATES), which can be used to store heat (higher than 50° Celsius) in aquifers which can be used later as a heat source. Energy can be also recovered by exploiting the height differences in water storage distribution tanks, such as a small-scale hydropower system [83].

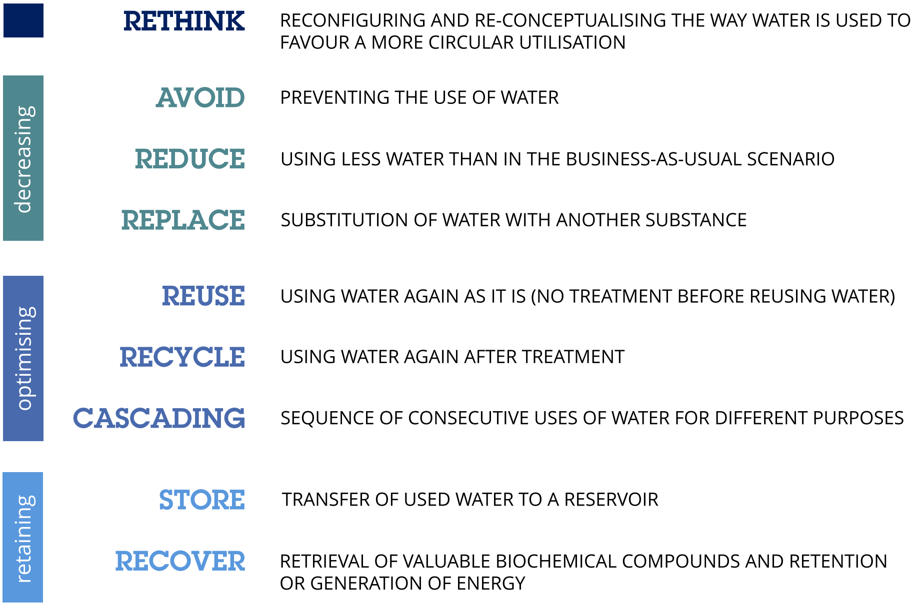
As a synthesis, Fig. 2 summarises the definition of each strategy for the CEW.

Although CEW strategies can work in isolation, solutions should be devised in an interrelated way as much as possible. This aspect is facilitated by the fact that water is in flux and is required in most if not all human activity. Linking different solutions requires coordinated actions at different levels and throughout all the stages of water usage [74]. It also requires the development of approaches in which the water output from a process can constitute an input for another process in an environmentally sustainable, socially and economically viable manner.

Conclusion: Prospects and Challenges for the CEW

A great deal of applied research has been published, but the theoretical understanding of the CEW is still developing, and the terminology is employed ambiguously. This study provides conceptual clarity and consistent terminology in order to further the transition to a fully fledged CEW. We argue that water is a unique element because it is a resource, a product and a service with no equivalent in the economic system and, as such, formulated a specific definition of the CEW with nine strategies — Rethink, Avoid, Reduce, Replace, Reuse, Recycle, Cascade, Store and Recover.

The CEW can serve as a basis for sustainable water management through water saving and efficient use and therefore contributes to many SDGs. In this context, CE



	RETHINK	RECONFIGURING AND RE-CONCEPTUALISING THE WAY WATER IS USED TO FAVOUR A MORE CIRCULAR UTILISATION
decreasing	AVOID	PREVENTING THE USE OF WATER
	REDUCE	USING LESS WATER THAN IN THE BUSINESS-AS-USUAL SCENARIO
	REPLACE	SUBSTITUTION OF WATER WITH ANOTHER SUBSTANCE
optimising	REUSE	USING WATER AGAIN AS IT IS (NO TREATMENT BEFORE REUSING WATER)
	RECYCLE	USING WATER AGAIN AFTER TREATMENT
	CASCADING	SEQUENCE OF CONSECUTIVE USES OF WATER FOR DIFFERENT PURPOSES
retaining	STORE	TRANSFER OF USED WATER TO A RESERVOIR
	RECOVER	RETRIEVAL OF VALUABLE BIOCHEMICAL COMPOUNDS AND RETENTION OR GENERATION OF ENERGY

Fig. 2 CEW strategies (no hierarchy implied)

strategies play a critical role in the establishment and application of CE solutions to water. That being said, CE strategies and solutions require favourable conditions if they are to be adopted successfully. As such, this study identifies three main challenges — normative, governance and implementation — that require further research and attention of policy makers to facilitate the transition to a full CEW.

Normative challenges refer to the need for new legislation or the revision of existing legislation. Legal norms are powerful tools for achieving transformative change; however, water legislation is generally complex, wide-ranging and fragmented, both nationally and internationally. The CE can be a way to upgrade and modernise current water legislation in the direction of greater integration across sectors. For this to happen, CEW concepts and strategies need to be implemented on the basis of a precise lexicon, as suggested in this paper. Normative aspects should consider enabling mechanisms such as a system of incentives and benefits for implementing CEW initiatives such as nutrient Recover or the use of disincentives like taxation to discourage wasteful linear processes. Moreover, new legislation should encompass international agreements to allow the promotion and development of transboundary CE strategies and solutions.

Governance challenges include the roles and responsibilities for the design and implementation of CEW strategies. It is crucial to expand the understanding and acceptance of the CE by all actors using water, for example, when water is recycled for multiple uses or employed consecutively by different actors in Cascading. Education, acceptance and engagement with respect to CEW strategies and solutions are very important for the achievement of this goal. Furthermore, governments and water authorities are responsible for designing the most effective water governance mechanisms and arrangements (such as centralised/decentralised; public, private, or mixed solutions) for the CEW in light of local specificities and contextual factors. A successful transition to the CEW implies the involvement of all relevant stakeholders, especially when Rethinking a system.

Implementation challenges include the barriers to, and opportunities for, a systematic application of the CEW. These challenges may be found where several strategies and solutions need to be combined, as in Cascading, or where existing conservative water management approaches result in a lock-in and path dependency that prevent the introduction of new solutions. In this regard, many CEW solutions at the pilot scale require adequate investments to achieve wide-scale application.

Exploiting synergies and the integration and coordination of multiple solutions are among the most important issues for future development. However, the CEW appears to be a perfect testing ground for learning and experimentation as it involves extensive innovation, whether of social, organisational or technological nature with knowledge sharing as a key component among actors and organisations. The establishment of a system of indicators and the related monitoring capabilities is fundamental to measure the progress of the CEW. Finally, implementation challenges should always include reducing environmental impacts while promoting environmentally viable CE solutions.

The normative, governance and implementation challenges should be urgently considered by policymakers and decision-makers at large. At the same time, researchers from a vast array of disciplines (such as law, ecology, governance, chemistry and engineering, to mention just a few) should contribute to these challenges through knowledge production, applied solutions and strategic advice.

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Declarations

Conflict of Interest The authors declare no competing interests.

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