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Research article

# Measuring urban water circularity: Development and implementation of a Water Circularity Indicator

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ABSTRACT

Urban Water Management (UWM) involves balancing the inflows and outflows of water such that water entering and leaving the system boundary reduces with time. Several frameworks and indicators have been formulated for UWM with a limited focus to achieve circularity of water flows at all the phases of the engineered urban water cycle. A novel indicator called 'Water Circularity Indicator' (WCI) is developed in this study to assess, monitor and improve the circularity of urban water flows. The WCI is derived from Material Circularity Indicator developed by Ellen McArthur Foundation and Granta design. In the current study, WCI is initially validated using 100 scenarios considering the variation of 5Rs, i.e., reduce, reuse, recycle, reclaim and restore. Further, WCI is compared with other indicators focusing on urban water management from the literature. The evaluation of results indicate that WCI correlates with most of the indicators selected for comparison. The WCI uses the water mass balance principle in its derivation and distinctively captures reuse, recycling, reclamation and restoration strategies in a single indicator value compared to other indicators. The WCI provides maximum information in a single indicator value ranging from 0 to 1.0. A higher value of WCI indicates lesser extraction of virgin water resources and wastewater disposal with maximum water circulation within the city under consideration. The novelty of WCI lies in its unique approach of considering all 5Rs and easy interpretation for decision-makers across multiple domains. WCI is recommended to be used by city authorities and policy makers for achieving water goals and for Circular Economy (CE) implementation. Policies can be formulated based on WCI to enhance CE in the water sector and reduce virgin water consumption, ultimately leading to water conservation.



## 1. Introduction

Water is a crucial resource for human consumption and the overall urban metabolism (Kennedy et al., 2011; Gandy, 2004). The quantity of water available is in balance in all its forms; but its quality and utilization efficiency are a matter of concern across the globe. With increasing urbanization, the quantity and quality of consumable water are deteriorating rapidly in major parts of the world (WRI (Water Resources Institute), 2019; Falkenmark and Widstrand, 1992). Urban water security is at risk, which impedes economic, environmental and social development (Hoekstra et al., 2018). Globally, it is revealed that 17 countries are in the 'extremely high water stress' category, i.e., more than 80% of available water is withdrawn for consumption (WRI (Water Resources Institute), 2019). Thus, there is a need to

*Abbreviations:* 4Rs, reuse, recycle, reclaim, restore; 5Rs, reduce, reuse, recycle, reclaim, restore; 6Rs, reduce, reuse, recycle, reclaim, recover, restore; C, volume of water consumed; CE, circular economy; $C_{Rc}$, fraction of water collected for reclamation; $C_{Re}$, fraction of water collected for recycling; $C_{Rst}$, fraction of water collected for restoration; $C_{Ru}$, fraction of water collected for reuse; CSR, centralized supply replaceability; EMF, Ellen MacArthur Foundation; $E_{Rc}$, usage efficiency in reclamation; $E_{Re}$, usage efficiency in recycling; $E_{Rst}$, usage efficiency in restoration; F(X), utility factor; $F_{Rc}$, fraction of water reclaimed from wastewater treatment facilities; $F_{Rd}$, fraction of water consumption reduced; $F_{Re}$, fraction of water recycled from wastewater treatment facilities; $F_{Rst}$, fraction of water restored to the stock; $F_{Ru}$, fraction of water reused; IRR, internal recycling ratio; L, fraction of total volume of water lost; LFI, linear flow index; MCI, material circularity indicator; $R_{st}$, volume of water restored; R, any of the reduce, reuse, recycle, reclaim, restore or recover activity; S, volume of freshwater supplied from the centralized and decentralized, surface as well as groundwater sources; TUR, total use replaceability; UWM, urban water management; UWOT, urban water optioneering tool; UWS, urban water system; V, actual virgin water consumed; $V_C$, volume of virgin water consumed; W, total volume of water discharged and released outside the system boundary; $W_0$, volume of untreated water generated; WCI, Water Circularity Indicator; $W_{Rc}$, volume of water wasted in reclamation; $W_{Re}$, volume of water wasted in recycling; $W_{Rst}$, volume of water wasted in restoration; WWPWS, Wastewater Potential for Water Supply; WWRtoWWT, ratio of reused wastewater to total wastewater treatment; WWTPs, wastewater treatment plants; WWTtoWW, ratio of wastewater treated by WWTPs to total wastewater volume discharged.

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replenish the already scarce water resources in order to allow a sufficient quantity of water available for consumption in present and future conditions.

Urban water management (UWM) involves freshwater extraction, treatment, and supply. After supply and consumption, the wastewater generated needs to be managed appropriately such that its maximum efficiency can be harnessed by retaining it longer in the loop. Responsible wastewater management can significantly contribute to the reduction in water stress conditions. Countries such as US (California, Arizona, Florida), Cyprus, France, Greece, Germany, Spain, Israel, Singapore, Australia are progressive examples where wastewater recycle and reuse has contributed exquisitely to meet the overall water demand (Angelakis and Gikas, 2014; Jiménez and Asano, 2008). Recycle, reuse, reclaim, originate from extract-use-reclaim-recycle-reuse thinking of Circular Economy (CE) against extract-use-dispose from the linear economy perspective of waste management (Winans et al., 2017). Voulvoulis (2018) and Sgroi et al. (2018) emphasized on the role of CE paradigm in wastewater reuse, thereby positively contributing towards the overall reduction in water resource scarcity. The concept of CE is gaining rapid attention in various sectors such as waste management, manufacturing, electronics and construction industry (Mhatre et al., 2021). CE implementation in the water sector has grown steadily in the past decade (Nika et al., 2020a; Smol et al., 2020). CE application involves balancing the water resources so that the water entering and leaving the system boundary reduces with time. The 6Rs (Reduce, Reuse, Recycle, Reclaim, Recover, Restore) strategies with a confluence of BS principles proposed by Kakwani and Kalbar (2020) can be efficiently implemented to enhance water circularity, ultimately reducing the virgin water demand. However, it is crucial to first prioritize the 6Rs strategies, followed by their operationalization and continuous monitoring. Operationalization of the strategies is possible using six British Standard, BS 8001, 2017 principles. Further, there is a lack of appropriate frameworks, indicators or sustainable indices for their prioritization and monitoring in the water sector.

Sustainability indices help in the policy-making process by assessing the progress made by a city, country or region towards attaining sustainability goals (Cucchiella et al., 2017; Parris and Kates, 2003). The indicators or indices also aid in conveying the information to the general public. However, formulation of such indices or indicators involve rigorous computations and steps (Singh et al., 2009). Within the CE framework, indicators facilitate the decision-making process by monitoring the development and prioritizing strategies that help achieve sustainability targets (Elia et al., 2017). Saidani et al. (2019) emphasized that assessment methods such as indicators can play a vital role in understanding CE and its implementation. Thus, aiding practitioners in various disciplines to set and achieve the comprehensive CE targets. In this regard, numerous studies have proposed frameworks, indices or indicators to move towards circularity in recent years (Kalmykova et al., 2017). As there is no single definition of CE (Kirchherr et al., 2017), the indicators defined in the past studies also differ in terms of usage, purpose, and scope (Parchomenko et al., 2019; Saidani et al., 2019).

Numerous frameworks or indicators have also been proposed in the water sector to preserve this valuable resource (Palme et al., 2005, Smol and Koneczna, 2021). However, the frameworks or indicators cover only a particular phase of urban water management/cycle (Collivignarelli et al., 2021); concentrate on one or two R out of the 6Rs (Preisner et al., 2022; van Schaik et al., 2021) or are region specific (Jeong and Park, 2020). Such frameworks or indicators are helpful when the objective is to assess a particular phase/stage or a process in the urban water sector, which can be beneficial only with the help of a holistic indicator.

Several approaches are being used as a framework for deriving indicators in the urban water sector. To name a few, Integrated Urban Water Management, Urban Water Cycle, Urban Water System (UWS), Urban Water Mass Balance, Urban Water Security, Water Sensitive Urban Design, Urban Water Metabolism, Urban Storm Water Management. The essence behind all the frameworks remains the same, i.e., sustainable UWM.

Urban water metabolism is one of the most extensively researched topics with the core idea of water mass balance and its valuation (Venkatesh et al., 2017; Renouf and Kenway, 2016). Within the urban water mass balance framework, several models or tools have been proposed, such as Aquacycle (Mitchell et al., 2001), UrbanCycle (Hardy et al., 2005), UWOT (Urban Water Optioneering Tool) (Makropoulos et al., 2008), WaterMet (Behzadian and Kapelan, 2015a), DMM (Dynamic Metabolism Model) (Venkatesh et al., 2017). The models proposed in past studies have also been reviewed for their application in the decision-making process (Bach et al., 2014; Urich and Rauch, 2014). Additionally, Kenway et al. (2011) proposed a methodology for evaluating urban metabolism based on water mass balance. The equations used in the framework comprised of anthropogenic and natural water flows to manage, monitor and account for water resources in a given system boundary. The basic urban water mass balance model was further modified and refined by Kenway and co-workers, emphasizing the need to achieve efficient UWM, including evaluation framework and indicators development (Renouf et al., 2017; Farooqui et al., 2016). Another group of researchers focused more on the modelling of urban water cycle using software and computational methods (Venkatesh et al., 2017; Rozos and Makropoulos, 2013;). The contribution of these studies in urban water mass balance or urban water metabolism literature is tremendous. However, the indicators proposed in the above-stated studies cannot be directly applied to efficiently implement and monitor CE in the water sector due to the following reasons:

i. The aim of evaluating circularity is to estimate the amount of water flowing in a circular manner, which is not focused directly in already developed indicators.
ii. The existing indicators account for both the anthropogenic/engineered flows and natural/hydrologic flows, which is not a suitable framework while evaluating water circularity (Arora et al., 2022).
iii. The indicators proposed in past studies are used to assess a particular phase or stage in UWM.

Thus, there is a need for appropriate indicator(s) to monitor the implementation of CE in urban water sector. Ellen MacArthur Foundation (EMF) in collaboration with Granta Design, developed a robust indicator called the Material Circularity Indicator (MCI), based on material flow analysis, to manage, improve, and monitor the CE practices for the decision-making process (EMF and Granta Design, 2015).

To extend this concept in the water sector, MCI is modified in the current study and a novel indicator termed as 'Water Circularity Indicator (WCI)' is developed. WCI will help the authorities to monitor and assess urban water goals, which will enhance and improve the CE implementation in the urban water sector. The WCI provides maximum information in a single indicator value with easy interpretation for decision-makers across multiple domains. Adopting WCI on a large scale can excessively help to reduce the virgin water demand. Through WCI, the percentage of water that is reduced, reused, recycled, reclaimed and restored can be obtained, and accordingly, benchmarking can be carried out. The novelty of the WCI proposed in this study lies in its ability to express the actual water situation in a simple yet comprehensive manner. Thus, WCI will help in policy implications targeted towards tackling water scarcity. The current study also compares the WCI with indicators proposed in past studies. The basic idea is to determine the efficacy of indicators for their performance in varying scenarios. The comparison with already developed indicators is intended to highlight the insights that WCI can provide as a single indicator.

This study also addresses several targets from UN Sustainable Development Goals (SDGs) such as SDG 6 (6.3, 6.4, 6.5, 6.6) and SDG 12 (12.2, 12.5). WCI supports SDG Target 6.3 by reducing the disposal of untreated wastewater into the water bodies and increasing the recycle and reuse activities; Target 6.4 by emphasizing efficient consumption of freshwater resources; Target 6.5 by efficient management of water resources and Target 6.6 by concentrating on restoration of waterbodies. Target 12.2 supports efficient management of natural resources, and our study emphasizes water resources. Target 12.5 promotes reduce, reuse and recycle strategies along with waste reduction, which is also highlighted in this study for the water sector.

The current article comprises of five sections wherein Section 2 provides a literature review on the CE indicators and water mass balance indicators. Section 3 includes the methodology on the derivation of WCI with its validation and evaluation. Section 4 discusses the results comparing previously developed indicators with WCI along with the advantages, limitations, and future scope followed by the conclusion in Section 5.

## 2. Literature review

The research community has extensively worked on the development of frameworks or indicators to assess the performance of CE implementation strategies (Merli et al., 2018; Sassanelli et al., 2019). In this regard, several indicators have been developed in recent years to enhance circularity (Corona et al., 2019; Moraga et al., 2019). The indicators are defined on the basis of implementation levels such as Micro – Products, components or materials; Meso – Businesses, industrial symbiosis; Macro – Cities, regions, nations (Nikolaou and Tsagarakis, 2021; Ghisellini et al., 2016). Other than indicators, similar terms such as metrics or indices have also been used in the literature for CE assessment, implementation, or monitoring (Harris et al., 2021). Single indicators such as Material Circularity Indicator (EMF and Granta Design, 2015), Zero Waste Index (Zaman and Lehmann, 2013), Reuse Potential (Park and Chertow, 2014), Resource Duration (Franklin-Johnson et al., 2016), Circular Economy Index (Di Maio and Rem, 2015), Circular Economy Performance (Huysman et al., 2017), Value-based Resource Efficiency (Di Maio et al., 2017) have been proposed; however, no consensus has been reached on the comprehensiveness of the indicators so far (Niero and Kalbar, 2019).

Subsequently, several frameworks and indicators have been progressively developed within the purview of the CE concept in the water sector for efficient monitoring and management of water resources (Arora et al., 2022; Nika et al., 2020b). Urban water metabolism focuses on the inflow and outflow of natural and anthropogenic water in the urban water cycle, extensively studied by the research community. Brown et al. (2009) proposed a framework that has been widely applied on urban water transitions, consisting of 'Water Cycle City' as one of the crucial components in UWM. Zhu and Chang (2020) utilized the urban water transition framework and proposed indicators for examining the growth of Shanghai from 2011 to 2017; however, only the rate of water use, water reuse and recycling was included in the Water Cycle City. Also, van Leeuwen et al. (2012) proposed 24 indicators called as City Blueprints for gauging the sustainability of the urban water cycle; however, a limited focus was given to wastewater and its potential for water supply which can aid in closing the water loop.

Kenway et al. (2011) proposed a framework on systematic urban water mass balance and defined a set of indicators to assess the performance of UWS. Later, Renouf and Kenway (2016) reviewed the evaluation frameworks for expanding urban water goals, emphasizing direct and indirect water usage. Also, Farooqui et al. (2016) provided a framework for analyzing the urban systems using engineered/anthropogenic and natural/hydrological water flows along with their interconnections. Correspondingly, urban water performance indicators were proposed based on achievable and aspirational objectives which were validated with the help of stakeholders (Renouf et al., 2017), and was further implemented on a city-region scale (Renouf et al., 2018). Refinement of the urban water mass balance indicators, initially developed by Kenway et al. (2011), was then carried out in the context of developing countries (Paul et al., 2018). The same group recently proposed a model called "Site-scale Urban Water Mass Balance Assessment (SUWMBA)" to estimate the potential of local conditions in achieving urban water balance (Moravej et al., 2021).

Utilizing indicators to develop overall assessment models has also been thoroughly worked on by the research community. Sustainability assessment using a tool called WaterMet$^2$ introduced by Behzadian and Kapelan (2015a) played an important role in modelling UWS. Furthermore, Landa-Cansigno et al. (2020) utilized WaterMet$^2$ to evaluate strategies related to water reuse with the urban water metabolism framework. To efficiently plan urban water infrastructure; it is beneficial to consider water, stormwater and wastewater systems collectively (overall water metabolism), including its sustainability assessment (Venkatesh et al., 2017; Behzadian and Kapelan, 2015b). Another tool UWOT developed by Makropoulos et al. (2008), can be used as a decision support tool to select options/strategies for sustainable UWM (Makropoulos and Rozos, 2011). The options/strategies are assessed based on the technology library embedded in the tool, followed by the evaluation of sustainability indicators, which is a data-intensive process. Later, Rozos and Makropoulos (2012) incorporated the role of localized rainwater harvesting and greywater recycling in sustainably managing the urban water cycle using UWOT which provided valuable insights. UWOT was further modified to simulate the complete water cycle from source to tap and back to the source (Rozos and Makropoulos, 2013). Assessment of the influence of small treatment units to supply treated wastewater for ecosystem services in reducing the overall temperature of the region under consideration was also analyzed using UWOT (Rozos et al., 2017). Comparison between centralized and distributed decentralized systems was then evaluated using key performance indicators to exhibit the benefits of circular neighborhoods (Bouziotas et al., 2019). Hence, it is evident that extensive research has been performed in urban water mass balance to reduce the burden on water resources and utilize them judiciously (Peña-Guzmán et al., 2017).

A comprehensive list of the indicators proposed in past studies based on water mass balance is provided in Table S1 in Supplementary Information – 01 (SI-01). Table S1 also includes information about the nature of flows considered (natural or anthropogenic) while deriving individual indicators along with their applicability to any of the 6Rs. However, as discussed in Section 1, there is a need for indicator(s) covering all the urban water cycle components, including the assessment of the existing or achievable level of circularity. Also, in UWS, natural and anthropogenic flows are interwoven to calculate the overall water balance. However, to the best of the authors' knowledge, the individual impact of the anthropogenic or engineered water flows in developing indicator(s) is not explicitly explored in previous studies.

Further, several studies show the potential of stormwater for water supply and rainwater harvesting at the household or decentralized level and are promoted extensively (Gleason Espíndola et al., 2018; Marteleira et al., 2014). In countries where rainfall occurs only during a few months of the year, most of the centralized reservoirs (dams) are filled or restored during the monsoon, along with the restoration of groundwater reservoirs. It can be considered that the rainwater is indirectly consumed throughout the year from centralized and decentralized sources. Hence, the contribution from rainwater is not directly considered in this work.

The motivation of the current study is to understand the role of engineered UWS in managing urban water demand to develop a novel indicator. The primary system boundary considered in this work is the water flowing through the pipes/sewers in an urban area or a city. Hydrological flows such as precipitation, evapotranspiration losses, infiltration losses and runoff are out of scope of the study. Fig. 1 depicts the major natural and anthropogenic flows in a given urban catchment

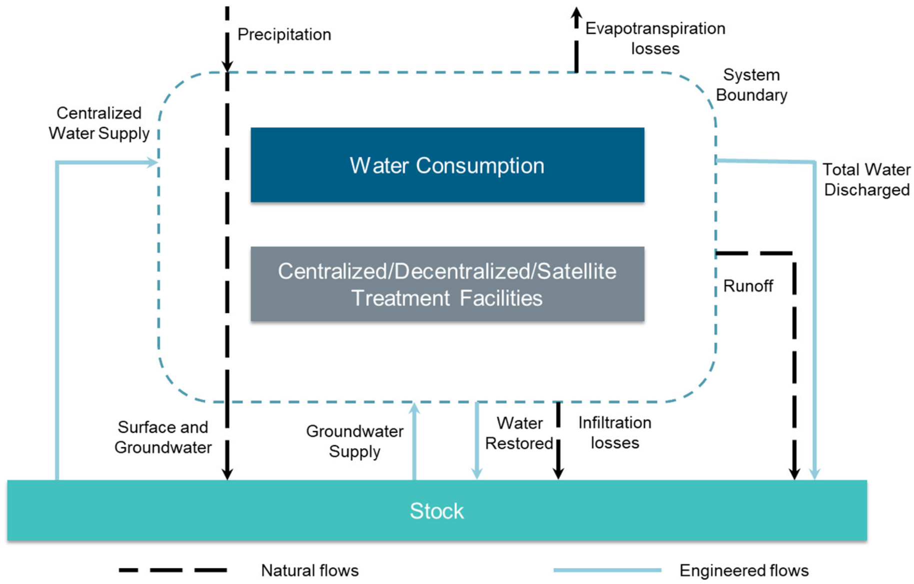



**Fig. 1.** Meta-diagram indicating system boundary and the scope of Water Circularity Indicator. Scope of the study considers only Engineered flows.

area. Since human intervention plays a crucial role in CE implementation (Arora et al., 2022), only anthropogenic/engineered flows are considered in this study. Flows such as centralized supply, groundwater supply, the water discharged and water restored are inside the scope of the study.

## 3. Methods

The methodology to derive WCI is inspired from the concept of MCI developed by Ellen McArthur Foundation and Granta Design (EMF and Granta Design, 2015). This section covers a brief introduction to MCI followed by a detailed expression of each term involved in the derivation of WCI. The assumptions that were considered for the development of WCI are also listed in this section. Further, validation of WCI is carried out using 100 scenarios replicating real-life situations, followed by its comparison and correlation with already established indicators from the literature.

### *3.1. Material circularity indicator*

EMF and Granta Design (2015) proposed a methodology to measure the material circularity (product/company level) based on material flow analysis. The method is designed for technical material with MCI values ranging from 0 to 1.0, where 0 indicates a completely linear system and 1.0 indicates a completely circular system. A completely linear system involves exclusive use of virgin raw materials, which get converted into waste at the end of the use phase, whereas a circular system would involve the use of recycled materials, thereby minimizing waste generation. The MCI for a component or material indicates the extent to which the linearity has been minimized and restorative flow/circularity has been maximized. The MCI derived is for a system wherein the recycled or reused feedstock can be obtained from the open market and collected for open supply. The representation of material flows in MCI can be referred from the original diagram provided in the methodology document by EMF and Granta Design (2015).

The equation to calculate MCI is given below

$$MCI = 1 - LFI \times F(X) \tag{1}$$

where

LFI – Linear Flow Index.

F(X) – Utility factor

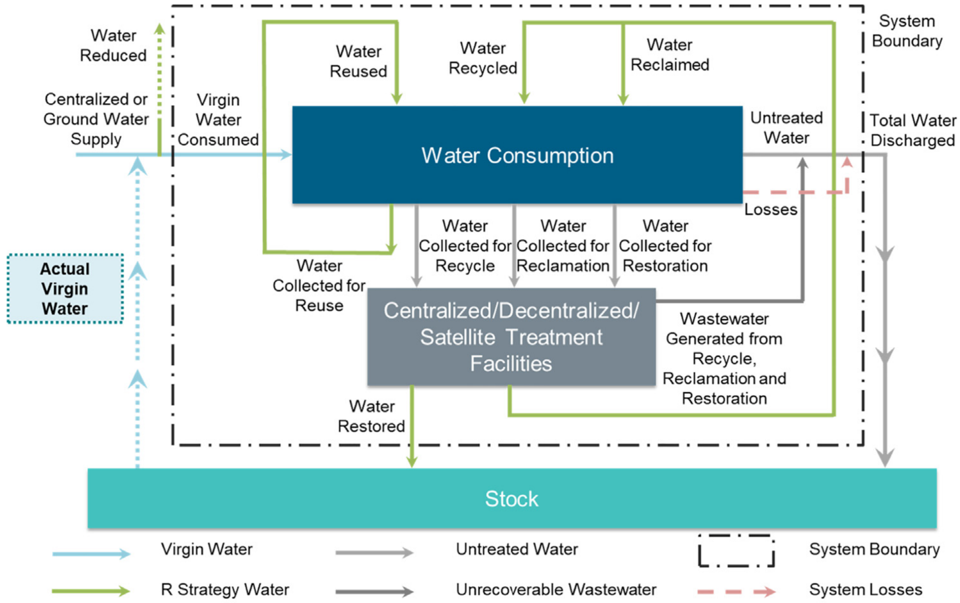
$$F(X) = \frac{0.9}{X} \tag{2}$$

LFI indicates the extent of linearity practiced with the value ranging from 0 to 1.0, which is further explained in Section 3.2.5. “X” is the product's utility and “F(X)” is the utility factor that influences MCI value based on the lifetime or usage. The detailed derivation of MCI can be referred from EMF and Granta Design (2015). MCI is originally designed for technical materials, and the focus of the current study is to extend its application in the water sector. As water does not change its form across the urban areas, it can be considered as technical material. Hence, the originally formed MCI is modified to WCI, as discussed in the following section.

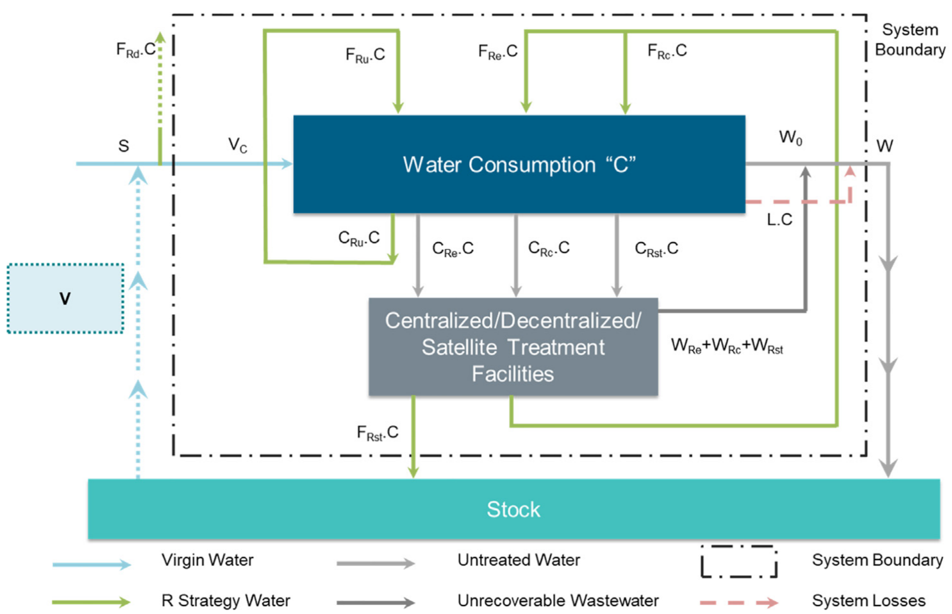
### *3.2. Water circularity indicator*

WCI is a modified form of MCI wherein water is used in place of a product and LFI along with the circularity of water in a given system boundary are evaluated. The indicator derived in this study involves engineered/anthropogenic urban water flows, and its interaction with natural/hydrological parameters is not considered. The recycle, reuse and reclamation activities take place inside the system boundary, whereas treated water that is restored and reduced are outside the system boundary. A diagrammatic representation of flows of water used to derive WCI is shown in Fig. 2, and the methodology to determine WCI is explained below.

The system boundary involves urban water consumption wherein freshwater (centralized and decentralized surface and groundwater sources) is supplied from outside the system boundary. All the wastewater treatment plants at centralized, decentralized, and satellite locations lie within the system boundary. Water flowing through pipe or sewer network i.e., through the engineered system for an urban area or a city, is considered as a system boundary. Stock includes all types of water bodies such as lakes, rivers, ponds, large storage reservoirs that are considered outside the system boundary. The decentralized groundwater sources such as bore-well/well are outside the system boundary in the form of stock. Total water consumed “C” inside system boundary is either the freshwater supplied by centralized or decentralized (surface or ground) water sources, or treated wastewater sources, i.e., the recycled as well as reclaimed water, and reused water




(a) WCI actual flows




(b) WCI notations

**Fig. 2.** System boundary and water flows considered to determine Water Circularity Indicator. Dotted lines indicate indirect flows. Stock includes all types of water bodies such as lakes, rivers, ponds, large storage reservoirs, which are considered outside the system boundary. Urban water consumption and wastewater treatment take place within the system boundary.

used without treatment. “$V_C$” is the volume of virgin water consumed within the system boundary (refer Fig. 2(b)).

“$W_0$” is the quantity of untreated water generated after consumption, excluding the wastewater collected for recycling “$C_{Re}$”, reclamation “$C_{Rc}$”, as well as restoration “$C_{Rst}$” and the water collected for reuse “$C_{Ru}$”. Wastewater collected is then treated as per desired standards depending on the end-use requirements. It is assumed that the wastewater is not generated in the reuse process. After treatment, water in the form of recycled water “$F_{Re}$” and reclaimed water “$F_{Rc}$” is sent back to the loop for consumption. Treated wastewater is also used for restoration purposes “$R_{st}$”, i.e., groundwater recharge, river, lake, or water body rejuvenation. Since the restored volume “$R_{st}$” of water goes back to stock, it is the volume of water to be deducted from virgin water consumed “$V_C$”. Thus, “V” is the actual volume of virgin water consumed (refer Fig. 2(b)).

After treatment, there can be 100% usage efficiency “$E_{Re}$”, “$E_{Rc}$”, “$E_{Rst}$” considering no wastewater generation i.e., complete utilization of treated water; or less efficiency based on the quantity of water collected for treatment and its utilization/consumption. Depending on the usage efficiency, wastewater generated from recycling “$W_{Re}$”, reclamation “$W_{Rc}$”, and restoration “$W_{Rst}$” is evaluated. Consumption of water also includes losses “L” in the form of human consumption losses, physical distribution losses, as well as evaporation losses during consumption. Thus, the total volume of water “W” going outside the system boundary includes untreated water, wastewater generated from recycling, reclamation and restoration activities, and losses (refer Fig. 2(b)). Apart from the interventions involving reuse, recycle, reclamation and restoration, reduce activity can also be performed by decreasing the volume of fresh water consumed/lost. Reduction in water consumption can be achieved through the application of water-efficient devices, raising consumer awareness, regular maintenance at the household and distribution level. Also, consumption of rainwater harvested at localized level can contribute to the reduction in freshwater utilization. Thus, an indirect contribution from rainwater in the form of "Reduce" can be considered. Ultimately, the total water consumed "C" is the water supplied "S" from which the volume of water reduced (i.e. "$F_{Rd}$.C") is deducted. Since WCI is based on water mass balance and one of the 6Rs, i.e., recovery, involves extraction of energy, nutrients and other materials; hence, the remaining 5Rs (reduce, reuse, recycle, reclaim, restore) are incorporated in the evaluation of WCI.

*3.2.1. Water consumption (C)*

The total water consumed inside the system boundary is obtained by deducting the reduced volume "$F_{Rd}$.C" of water consumed to the total volume of water supplied "S".

$$Supply\ (S) = Population \times Demand$$

Demand varies based on norms applied by the urban water utilities, which should be considered before estimating the volume of water to be supplied. Thus, the volume of total water consumed "C" can be calculated as

$$C = S - F_{Rd}.C \tag{3}$$

which can also be written as

$$C = \frac{S}{1 + F_{Rd}} \tag{4}$$

where

C – Volume of water consumed.

S – Volume of freshwater supplied from the centralized and decentralized, surface as well as groundwater sources.

$F_{Rd}$ – Fraction of water consumption reduced.

*3.2.2. Virgin water consumed ($V_C$)*

Generally, water is supplied through a centralized system in urban areas and is extracted from surface water reservoirs or groundwater storage. At decentralized locations, water is extracted from groundwater sources such as bore-well/wells. The total fresh/virgin water supplied to the city is calculated as given in Eq. (5).

$$V_C = C \times (1 - F_{Ru} - F_{Re} - F_{Rc}) \tag{5}$$

where

$V_C$ – Volume of virgin water consumed.

C – Volume of water consumed.

$F_{Ru}$ – Fraction of water reused.

$F_{Re}$ – Fraction of water recycled from wastewater treatment facilities.

$F_{Rc}$ – Fraction of water reclaimed from wastewater treatment facilities.

CE emphasizes declining virgin water extraction by enhancing the activities such as reduce, reuse, recycle, and reclamation, thereby reducing the water discharged from the system boundary. Also, actual virgin water "V" is different from the virgin water consumed "$V_C$", as explained further in Eq. (15).

*3.2.3. Total water discharged (W)*

The wastewater generated in an urban area includes the volume of water consumed "C" excluding the volume of water collected for reuse "$C_{Ru} \cdot$C", recycle "$C_{Re}$.C", reclamation "$C_{Rc}$.C", restoration "$C_{Rst}$.C" and the volume of water lost "L.C". Generally 60–95% of the water supplied, gets converted to wastewater depending on climate conditions and usage (Butler and Davies, 2000; Sahely and Kennedy, 2007); therefore, the return factor of 80% can be assumed in this study (Central Public Health and Environmental Engineering Organization (CPHEEO), 2013). Thus, losses can be considered to be around 20% subject to change in the study area. The volume of untreated water discharged can be calculated as:

$$W_0 = C \times (1 - L - C_{Ru} - C_{Re} - C_{Rc} - C_{Rst}) \tag{6}$$

where

$W_0$ – Volume of untreated water generated.

L – Fraction of total volume of water lost = 0.20.

$C_{Ru}$ – Fraction of water collected for reuse.

$C_{Re}$ – Fraction of water collected for recycling.

$C_{Rc}$ – Fraction of water collected for reclamation.

$C_{Rst}$ – Fraction of water collected for restoration.

It is assumed that there are no losses in the reuse process, i.e., water collected for reuse is utilized completely within the system boundary. The water collected for recycling, reclamation, and restoration purposes may not be completely utilized and might end up getting discharged into the natural environment. Thus, it is important to consider the usage efficiency in the respective processes. The equations used to determine water wasted in the recycling, reclamation, and restoration processes are given by:

$$W_{Re} = C \times (1 - E_{Re}) \times C_{Re} \tag{7}$$

$$W_{Rc} = C \times (1 - E_{Rc}) \times C_{Rc} \tag{8}$$

$$W_{Rst} = C \times (1 - E_{Rst}) \times C_{Rst} \tag{9}$$

where

$W_{Re}$ – Volume of water wasted in recycling.

$W_{Rc}$ – Volume of water wasted in reclamation.

$W_{Rst}$ – Volume of water wasted in restoration.

$E_{Re}$ – Usage efficiency in recycling.

$E_{Rc}$ – Usage efficiency in reclamation.

$E_{Rst}$ – Usage efficiency in restoration.

Efficiencies can be calculated using the following equations:

$$E_{Re} = 1 - \frac{C_{Re} - F_{Re}}{C_{Re}} \tag{10}$$

$$E_{Rc} = 1 - \frac{C_{Rc} - F_{Rc}}{C_{Rc}} \tag{11}$$

$$E_{Rst} = 1 - \frac{C_{Rst} - F_{Rst}}{C_{Rst}} \tag{12}$$

where

$F_{Rst}$ – Fraction of water restored to the stock.

The above equations are valid only if $C_{Re}$, $C_{Rc}$, $C_{Rst} > 0$, else, $E_{Re}$, $E_{Rc}$, $E_{Rst} = 0$. Thus, the total volume of water discharged from the given system boundary is as given below:

$$W = W_0 + W_{Re} + W_{Rc} + W_{Rst} + (L.C) \tag{13}$$

where

W – Total volume of water discharged and released outside the system boundary.

#### 3.2.4. Actual virgin water (V)

As per Fig. 2(a), some amount of treated wastewater is sent back to the ambient water environment (Stock). Here "$R_{st}$" is the volume of water restored and "$F_{Rst}.C$" is the volume of water leaving the system boundary for groundwater recharge, river or water body rejuvenation.

$$R_{st} = F_{Rst}.C \tag{14}$$

This quantity of water is also required to be deducted from the virgin water consumed "$V_c$". Therefore, actual virgin water "V" can be calculated as

$$V = V_C - R_{st} \tag{15}$$

where

V – Actual virgin water consumed.

#### 3.2.5. Linear flow index (LFI)

LFI determines the proportion of material flowing in a linear system, i.e., extracted/obtained from virgin resources and end up in landfills or remain unrecovered. Using the same analogy in the context of urban water sector, LFI estimates the proportion of water flowing in a linear approach against the implementation of the 5Rs strategy. It is the ratio of water flowing in a linear manner to the total water consumed inside the system boundary. It is calculated as follows:

$$LFI = \frac{V + W}{2C} \tag{16}$$

Since "V" and "W" include the volume of water flowing in a linear manner, the purpose is to reduce "V" and "W" as much as possible and increase the fraction of 5Rs, thus decreasing LFI. The denominator comprises of "2C", to avoid double accounting since two separate phases are considered, i.e., the consumption and disposal phase (refer Fig. 3). LFI ranges from 0 to 1.0, wherein 1.0 indicates a completely linear system and 0 indicates a completely circular system.

#### 3.2.6. Water circularity indicator (WCI)

WCI is the modified form of MCI, indicating the extent to which circularity is achieved for a given system. The equation to calculate MCI is given in Section 3.1 and using a similar analogy, the equation to calculate WCI is as follows:

$$WCI = 1 - LFI \times F(X) \tag{17}$$

In MCI, F(X) determines the influence of the product's utility. It is ideally designed to penalize the products with short lifetimes and poor utilization, and vice versa. However, in the context of water sector, the analogy of the industry-average lifetime of water is not applicable and hence the impact of utility is not considered due to which F(X) is excluded from WCI. The WCI can be calculated as:

$$WCI = 1 - LFI \tag{18}$$

The WCI value ranges from 0 to 1.0, 0 indicates a completely linear water cycle, i.e., freshwater extraction, consumption, and wastewater disposal without treatment, and 1.0 indicates a completely circular water cycle. However, a WCI value of 1.0 is not possible since there will always be some unavoidable losses related to human consumption. Thus, WCI plus losses will make a value equal to 1.0. As per the proposed WCI, in the ideal scenario of complete CE realization, there will always be some losses that are assumed to be 0.2, which result in WCI operating range from 0 to 0.8.

#### 3.2.7. Assumptions

In deriving WCI, following assumptions are made,

- The WCI is applicable only for anthropogenic flows and for a system where the water is reused, recycled or reclaimed, within the system boundary.
- It is assumed that there are no losses in the reuse process which is in line with the assumption used to derive MCI.
- One of the 6Rs, i.e., recovery, is not included in the calculation of WCI. It is related to the extraction of energy and materials that do not significantly affect the water mass balance within the system boundary.
- The quality of water obtained from recycling, reclamation, and restoration is as per the desired standards.

### 3.3. Material Circularity Indicator versus Water Circularity Indicator

The WCI is derived and modified based on the originally developed MCI. Table 1 highlights the major differences in the derivation of MCI and the proposed WCI. Considering the urban water flows, three more

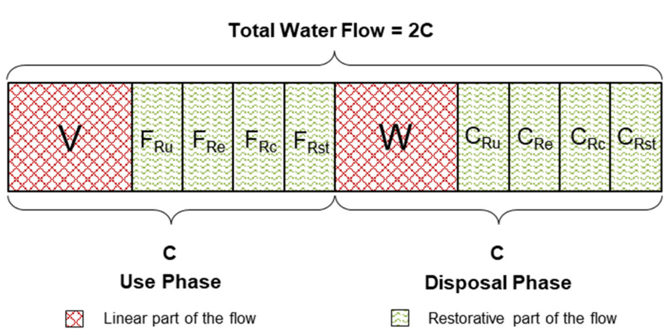



**Fig. 3.** Derivation of the Linear Flow Index (LFI) incorporating linear as well as restorative flows. V – Actual virgin water; W – Total water discharged; $F_{Ru}$ – Fraction of water reused; $F_{Re}$ – Fraction of water recycled from wastewater treatment facilities; $F_{Rc}$ – Fraction of water reclaimed from wastewater treatment facilities; $F_{Rst}$ – Fraction of water restored from wastewater treatment facilities; $C_{Ru}$ – Fraction of water collected for reuse purpose; $C_{Re}$ – Fraction of water collected for recycle purpose; $C_{Rc}$ – Fraction of water collected for reclamation purpose; $C_{Rst}$ – Fraction of water restored to the environment or stock.

**Table 1**
Comparison between Material circularity indicator and the proposed water circularity indicators highlighting the differences in equations.

| Sr. no. | Material Circularity Indicator | Water Circularity Indicator |
|---|---|---|
| i | $V = \boldsymbol{M} \times (1 - \boldsymbol{F_R} - \boldsymbol{F_U})$<br><br>V – Virgin material used in product<br>M – Total mass of material used in the product<br>$F_R$ – Fraction feedstock obtained from recycled material<br>$F_U$ – Fraction feedstock obtained from reused material | $V_c = \boldsymbol{C} \times (1 - \boldsymbol{F_{Ru}} - \boldsymbol{F_{Re}} - \boldsymbol{F_{Rc}})$<br><br>$\boldsymbol{C} = \frac{\boldsymbol{S}}{1+\boldsymbol{F_{Rd}}}$<br><br>$V = \boldsymbol{V_c} - (\boldsymbol{F_{Rst}}.\boldsymbol{C})$ |
| ii | $W_0 = M \times (1 - \boldsymbol{C_R} - \boldsymbol{C_U})$<br>$W_0$ – Waste that cannot be recovered<br>$C_R$ – Fraction of product mass collected for recycling<br>$C_U$ – Fraction of product mass collected for reuse | $W_0 = C \times (1 - \boldsymbol{L} - \boldsymbol{C_{Ru}} - \boldsymbol{C_{Re}} - \boldsymbol{C_{Rc}} - \boldsymbol{C_{Rst}})$ |
| iii | $W_C = M \times (1 - \boldsymbol{E_C}) \times \boldsymbol{C_R}$<br>$W_C$ and $W_F$ – Recycling wastes<br>$E_C$ and $E_F$ – Recycling efficiencies | $W_{Re} = C \times (1 - \boldsymbol{E_{Re}}) \times \boldsymbol{C_{Re}}$<br>$W_{Rc} = C \times (1 - \boldsymbol{E_{Rc}}) \times \boldsymbol{C_{Rc}}$<br>$W_{Rst} = C \times (1 - \boldsymbol{E_{Rst}}) \times \boldsymbol{C_{Rst}}$ |
| iv | $W = W_0 + \frac{\boldsymbol{W_F}+\boldsymbol{W_C}}{\boldsymbol{2}}$<br>W – Total waste generated | $W = W_0 + \boldsymbol{W_{Re}} + \boldsymbol{W_{Rc}} + \boldsymbol{W_{Rst}} + (\boldsymbol{L}.\boldsymbol{C})$ |
| v | $LFI = \frac{V+W}{2M}$ | $LFI = \frac{V+W}{2C}$ |
| vi | $MCI = 1 - LFI \times \boldsymbol{F}(\boldsymbol{X})$<br>F(X): Utility factor | $WCI = 1 - LFI$ |

Note: The terms used to derive MCI are only expressed in Table 1 and are not discussed anywhere in the article. Also, the MCI terms are not introduced at the article's beginning, to avoid confusion with the similar terms used in WCI. For more information on the derivation of MCI refer to EMF and Granta Design, 2015.

R terms, i.e. reduce, reclamation and restoration, are added in the original MCI derivation. Also, as discussed in Section 3.2.6 for urban water cycle, the notion utility factor is insignificant; hence, neglected in deriving WCI. Except for these major differences, the essence behind deriving the terms used in WCI compared to that in MCI remains the same.

### 3.4. Validation and Evaluation of Water Circularity Indicator

As discussed above, WCI is proposed as an indicator to quantify the water circularity in the urban water sector. Initially, to validate the WCI, 100 scenarios were generated (using random numbers) that represent variations in all the 5Rs according to real-life situations. The findings from 100 scenarios are adequate to express the impacts on WCI as the results on extending the analysis beyond 100 scenarios showed a similar trend in the WCI values. The scenarios are designed for any urban area or city where WCI can be used for the planning and monitoring of CE practices. In the present study, one million population was considered for the analysis, which can be modified based on the study area requirements. The water demand of 135 liters per capita per day (LPCD) for cities (Central Public Health and Environmental Engineering Organization (CPHEEO), 1999) was utilized in scenarios. Scenarios with random variation in the fraction of reduce, reuse, recycle, reclaim, and restore having the sum of all the 5Rs less than 0.8 (refer Section 3.2.3) were generated. Losses were considered to be 0.2 (refer Section 3.2.3); it is assumed that there is no loss of water during the treatment and the usage efficiency is 100%. WCI was computed for all the 100 scenarios using Eq. (18).

Then, to validate the advantages of using WCI, it was compared with other relevant established indicators shortlisted from Table S1 (SI-01), which are enlisted in Table 2. Indicators used in these studies evaluate the status of UWS having similar objectives as that of WCI. The equations for shortlisted indicators in Table 2 are expressed with the help of parameters used in the formulation of WCI (refer Fig. 2(b)). The original analogy behind the indicator remains the same, but the difference lies in the terminologies or parameters used. From the indicators listed in Table 2, only the highlighted indicators were used for the comparison as other indicators had a similar logic. To evaluate the indicators, the units for all the volumetric parameters i.e., C, V, $V_c$, W, $W_0$, $W_{Re}$, $W_{Rc}$, $W_{Rst}$, were same i.e., million liters per day (MLD) and all the other parameters are fractional with no units. Since the equations used to evaluate the indicators are in fractional format, normalization was not needed to compare indicators.

To understand the relationship between WCI and other indicators having similar objectives of achieving water circularity or water mass balance, Pearson's correlation coefficient was evaluated. LFI was discarded from the list of selected indicators provided in Table 2 because it is inversely proportional to WCI. Also, TUR (Total Use Replaceability) was removed from the list of indicators because the basic objective of TUR and WWPWS (Wastewater Potential for Water Supply) is the same. Thus, a total of six indicators, i.e., WCI, CSR (Centralized Supply Replaceability), WWPWS, IRR (Internal Recycling Ratio), WWTtoWW (Ratio of Wastewater Treated by WWTPs to total Wastewater volume discharged) and WWRtoWWT (Ratio of Reused Wastewater to Total Wastewater Treatment) were correlated using 100 scenarios.

## 4. Results and discussion

This section describes the variation of 5Rs and WCI for 100 scenarios discussed in Section 3. Interpretation of WCI with the help of graphical representation for all the scenarios sorted in increasing order of WCI and the related discussion is carried out. Further, three selected scenarios are explained for validation of WCI values along with the variation in each R and related values of other indicators. Evaluation results from the correlation analysis between all the selected indicators and WCI are also discussed. Each R captured by indicators is discussed and compared with WCI, followed by the advantages and limitations of WCI.

### 4.1. Validation of Water Circularity Indicator

The 100 scenarios were used to evaluate WCI values with the variation of all 5Rs, as discussed in Section 3.3. All the 100 scenarios and the variation of 5Rs are provided in Supplementary Information – 02 (SI-02). The scenarios are sorted in increasing order of the sum of 4Rs, i.e., reuse, recycle, reclaim and restore. Fig. 4 shows that with an increase in the sum of fractions of 4Rs, WCI value increases. However, variation in the fraction of 'reduce' does not affect WCI because $F_{Rd}$ is not accounted for inside the system boundary, as shown in Fig. 2(b). The uniqueness of WCI lies in the fact that when the usage efficiency is 100%, the sum of the fractions of 4Rs is equal to the WCI value.

Validation of the WCI for water mass balance and its variation with the fraction of water reduced, reused, recycled, reclaimed, and restored, is described with the help of three scenarios (24, 97 and 100) as given in Table 3. The scenarios were selected based on the changes in each R and the impact on WCI to present maximum information about WCI and shortlisted indicators. Sample calculations to evaluate WCI are highlighted in SI-02 (WCI-Calculations).

In S24, the sum of fractions reused ($F_{Ru} = 0.047$), recycled ($F_{Re} = 0.166$), reclaimed ($F_{Rc} = 0.024$) and restored ($F_{Rst} = 0.047$) contribute to a WCI value of 0.284, which is less as compared to the WCI value in S97 (0.783) or S100 (0.735). The higher value of WCI in S97 and S100 indicates that a larger quantity of water is recirculated in the form of reuse, recycle, reclamation and restoration activities as compared to that in S24. Also, the fraction of water reduced ($F_{Ru}$) is

**Table 2**
List of selected indicators based on the relationship with water mass balance considered in this study.

| Sr. no. | Indicator | Abbreviation | Original equation | Equation as per Fig. 2 notations | Source |
|---|---|---|---|---|---|
| 1 | Linear Flow Index | LFI | $LFI = \frac{V+W}{2M}$ | $LFI = \frac{V+W}{2C}$ | Present study |
| **2** | **Water Circularity Indicator** | **WCI** | $\mathbf{MCI = 1 - LFI \times F(X)}$ | $\mathbf{WCI = 1 - LFI}$ | **Present study** |
| **3** | **Centralized Supply Replaceability** | **CSR** | $\frac{\textbf{Wastewater flow}}{\textbf{Water supplied from centralized source}}$ | $\frac{\mathbf{W_0+W_{Re}+W_{Rc}+W_{Rst}}}{\textbf{Centralized Supply}}$ | **(Paul et al., 2018)** |
| 4 | Total Use Replaceability | TUR | $\frac{\text{Wastewater flow}}{\text{Total water used}}$ | $\frac{W_0+W_{Re}+W_{Rc}+W_{Rst}}{C}$ | (Paul et al., 2018) |
| **5** | **Wastewater Potential for Water Supply** | **WWPWS** | $\frac{\textbf{Wastewater flow}}{\textbf{Total water used}}$ | $\frac{\mathbf{W_0+W_{Re}+W_{Rc}+W_{Rst}}}{\mathbf{C}}$ | **(Ghosh et al., 2019)** |
| **6** | **Internal Recycling Ratio** | **IRR** | $\frac{\textbf{Volume of water recycled internally}}{\textbf{Total volume of water supplied to meet demand}}$ | $\frac{\mathbf{C\times(F_{Ru}+F_{Re}+F_{Rc})}}{\mathbf{C}}$ | **(Meng and Kenway, 2018)** |
| **7** | **Ratio of Wastewater Treated by WWTPs to total Wastewater volume discharged** | **WWTtoWW** | $\frac{\textbf{Wastewater treated}}{\textbf{Total wastewater volume discharged}}$ | $\frac{\mathbf{C\times(C_{Re}+C_{Rc}+C_{Rst})}}{\mathbf{W_0+W_{Re}+W_{Rc}+W_{Rst}+C\times(C_{Re}+C_{Rc}+C_{Rst})}}$ | **(Chu et al., 2015)** |
| **8** | **Ratio of Reused Wastewater to Total Wastewater Treatment** | **WWRtoWWT** | $\frac{\textbf{Reused Wastewater}}{\textbf{Total wastewater treatment}}$ | $\frac{\mathbf{C\times(F_{Re}+F_{Rc})}}{\mathbf{C\times(C_{Re}+C_{Rc}+C_{Rst})}}$ | **(Chu et al., 2015)** |

WWTPs – Wastewater treatment plants.
Bold entried in table 2 are the indicators that are selected for further analysis.

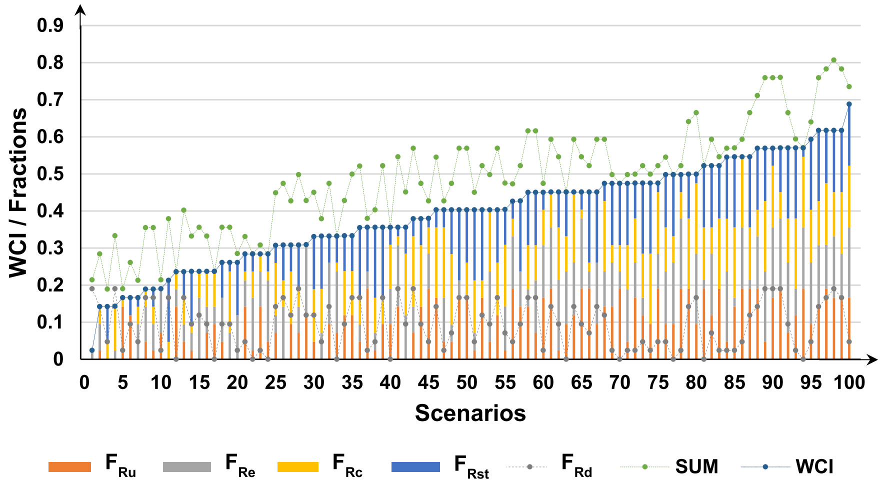



**Fig. 4.** Variation of Water circularity indicator (WCI) in 100 scenarios with 5Rs (reduce, reuse, recycle, reclaim, restore); $F_{Rd}$ – Fraction of water consumption reduced; $F_{Ru}$ – Fraction of water reused; $F_{Re}$ – Fraction of water recycled from wastewater treatment facilities; $F_{Rc}$ – Fraction of water reclaimed from wastewater treatment facilities; $F_{Rst}$ – Fraction of water restored from wastewater treatment facilities; Sum – $F_{Rd} + F_{Ru} + F_{Re} + F_{Rc} + F_{Rst}$).

zero in S24, causing an insignificant effect on the value of C (135.00 MLD). The total water consumed (C) inside the system boundary is dependent on the fraction of water that can be reduced ($F_{Rd}$) by various interventions, as discussed in Section 3.2. With the decrease in the fraction of water reduced ($F_{Rd}$), the total water consumption (C) increases and vice versa. Therefore, in S24 a higher quantity of virgin water (V = 96.66 MLD) is extracted and more untreated water is disposed ($W_0$ = 69.66 MLD) out of the system boundary.

Contrastingly, in S97 the WCI (0.667) is higher than S24 because of increased recirculation in the form of fractions of water reused ($F_{Ru}$ = 0.190), recycled ($F_{Re}$ = 0.119), reclaimed ($F_{Rc}$ = 0.166) and restored ($F_{Rst}$ = 0.142), and also lesser volume of water is consumed (C = 115.78 MLD) because in this scenario, fraction reduced ($F_{Rd}$) is 0.166. Increased circularity (WCI = 0.667), reduced virgin water consumption (V = 44.34 MLD) and reduced untreated water generation ($W_0$ = 21.19 MLD) is evident in S97. On the contrary, as compared to S97 fraction reduced ($F_{Rd}$ = 0.047) is lower in S100 and sum of fraction of all the 4Rs is higher (0.682); still the WCI value of S100 (0.682) is higher than that of S97. Hence, it should be noted that $F_{Rd}$ doesn't impact the WCI value.

### 4.2. Evaluation of Water Circularity Indicator

The selected indicators from Table 2 are compared and correlated with each other to understand their relationship. Also, the equations are provided in Table 2 for all the indicators for a better understanding of the associated parameters. Results of the correlation analysis are presented in Fig. 5, revealing a perfect negative correlation

**Table 3**
Selected scenarios for case-specific explanation.

| Known parameters | Description | Scenario 24 S24 | Scenario 97 S97 | Scenario 100 S100 |
|---|---|---|---|---|
| S (Liter/day) | Volume of freshwater supplied | $135 \times 10^6$ | $135 \times 10^6$ | $135 \times 10^6$ |
| C (MLD) | Volume of water consumed | 135.00 | 115.78 | 128.94 |
| $F_{Rd}$ | Fraction of water consumption reduced | 0.000 | 0.166 | 0.047 |
| $F_{Ru}$ | Fraction of water reused | 0.047 | 0.190 | 0.166 |
| $F_{Re}$ | Fraction of water recycled from wastewater treatment facilities | 0.166 | 0.119 | 0.190 |
| $F_{Rc}$ | Fraction of water reclaimed from wastewater treatment facilities | 0.024 | 0.166 | 0.166 |
| $F_{Rst}$ | Fraction of water restored from wastewater treatment facilities | 0.047 | 0.142 | 0.166 |
| $C_{Ru}$ | Fraction of water collected for reuse purpose | 0.047 | 0.190 | 0.166 |
| $C_{Re}$ | Fraction of water collected for recycle purpose | 0.166 | 0.119 | 0.190 |
| $C_{Rc}$ | Fraction of water collected for reclamation purpose | 0.024 | 0.166 | 0.166 |
| $C_{Rst}$ | Fraction of water restored to the environment or stock | 0.047 | 0.142 | 0.166 |
| **Derived parameters/indicators** | **Description** | **Scenario 24 S24** | **Scenario 97 S97** | **Scenario 100 S100** |
| Sum ($F_{Rd} + F_{Ru} + F_{Re} + F_{Rc} + F_{Rst}$) | | 0.284 | 0.783 | 0.735 |
| $W_{Re}$, $W_{Rc}$, $W_{Rst}$ (MLD) | Volume of water wasted in recycling, reclamation and restoration | 0.00 | 0.00 | 0.00 |
| V (MLD) | Actual virgin water | 96.66 | 44.34 | 40.23 |
| $W_0$ (MLD) | Volume of untreated water generated | 69.66 | 21.19 | 14.44 |
| W (MLD) | Total water discharged | 96.66 | 44.34 | 40.23 |
| LFI | Linear flow index | 0.716 | 0.383 | 0.312 |
| WCI | Water circularity indicator | 0.284 | 0.617 | 0.688 |
| CSR | Centralized supply replaceability | 0.688 | 0.244 | 0.149 |
| WWPWS | Wastewater potential for water supply | 0.516 | 0.183 | 0.112 |
| IRR | Internal recycling ratio | 0.237 | 0.475 | 0.522 |
| WWTtoWW | Ratio of wastewater treated by WWTPs to total wastewater volume discharged | 0.315 | 0.700 | 0.823 |
| WWRtoWWT | Ratio of reused wastewater to total wastewater treatment | 0.802 | 0.667 | 0.682 |

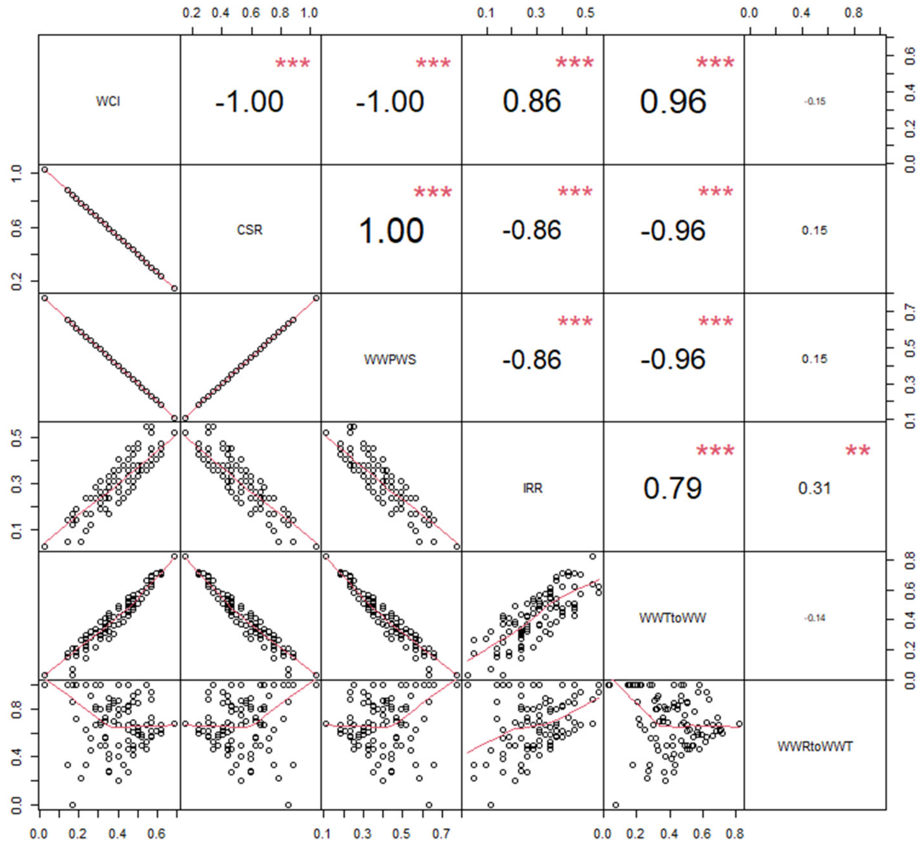



**Fig. 5.** Correlation between WCI and other selected indicators. WCI – Water circularity indicator; CSR – Centralized supply replaceability; WWPWS – Wastewater potential for water supply; IRR – Internal recycling ratio; WWTtoWW – Ratio of wastewater treated by WWTPs to total wastewater volume discharged; WWRtoWWT – Ratio of reused wastewater to total wastewater treatment. *p*-values (***: $p < 0.1\%$, **: $p < 1\%$, *: $p < 5\%$).

between WCI and CSR which can be attributed to the fact that with the increase in treatment and recycling, wastewater generation reduces, ultimately decreasing the CSR values. Similarly, WWPWS as an indicator evaluates the quantity of wastewater that can be utilized to replace the freshwater demand. Thus, with the reduction in wastewater generation, WWPWS also reduces, depicting a perfect negative correlation with WCI.

IRR is related to the quantity of wastewater that is recycled from the total wastewater generated. With the increase in reuse, recycle and reclamation activities, the value of the IRR increases. Thus, a significant positive correlation exists between WCI and IRR. However, in addition to each R captured by IRR, i.e., reuse, recycle, reclaim; WCI also captures the quantity of water restored; thus, the value of IRR slightly deviates from WCI.

Similarly, there exists a significant positive correlation between WCI and WWTtoWW; the value of both the indicators increases with the increase in treatment fraction. However, the reuse fraction is not captured by WWRtoWW as it does not undergo treatment. Enhanced treatment is beneficial for overall sustainability; however, WWRtoWWT evaluates the ratio of water reused to total wastewater treated, presenting no significant correlation with WCI, as shown in Fig. 5. Since the volume of water restored is treated but not consumed inside the system boundary, it negatively impacts WWRtoWWT and benefits WCI.

Along with the variation in each R and WCI values, Table 3 also provides variation in the values of the shortlisted indicators. In S24, reuse, recycle, reclamation and restoration activities are minimum and hence, there is more scope for wastewater to replace freshwater supply ($W_0 = 69.66$ MLD); hence CSR (0.688) and WWPWS (0.516) values are relatively higher. Since CSR and WWPWS are also negatively correlated with WCI, an increase in WCI value in S97 and S100 resulted in a decrease in CSR and WWPWS as less wastewater is available to be replaced. Paul et al. (2018) proposed CSR and Ghosh et al. (2019) proposed WWPWS indicator to assess the potential of wastewater to replace centralized supply but didn't capture the reuse and restoration components. However, WCI efficiently captures the reuse and restoration components, including recycle and reclamation.

The IRR value is slightly less than the WCI value in all the scenarios, as IRR doesn't capture the restoration component. On the contrary, the WWTtoWW value is more than the WCI value in all the scenarios because it considers the total quantity of wastewater treated from the total wastewater generated without considering the reuse component. IRR proposed by Meng and Kenway (2018) concentrated on water mass balance in designing water-sensitive UWS for internal flows recirculation with a lesser focus on the potential of treated wastewater that can be restored. Similarly, WWTtoWW proposed by Chu et al. (2015) emphasized on structure and efficiency based indicators to evaluate the performance of the urban water cycle but did not consider reuse component in the overall framework.

In S97, the value of WWRtoWWT (0.667) is lesser and the sum of wastewater recycled (0.119) and reclaimed (0.166) is higher than that in S24. Although the fraction restored (0.142) and reused (0.190) are higher in S97 as compared to S24, the reduction in value of WWRtoWWT (from 0.802 to 0.667) is due to the water recycled and reclaimed but not restored. This reduction in the value of WWRtoWWT signifies that more water is treated ($C_{Re} + C_{Rc} + C_{Rst} = 0.427$), but less water is utilized ($F_{Re} + F_{Rc} = 0.285$) inside the system boundary. Also, WWRtoWWT does not capture the reuse component. Hence, it is important to emphasize that WWRtoWWT is less correlated with WCI and it behaves differently in all the scenarios.

Overall, CSR, WWPWS and WWRtoWWT do not capture reuse and restoration components, IRR does not capture restoration component, and WWTtoWW does not capture reuse components. Thus, it can be asserted that WCI captures the impact of all 4Rs, which is of enormous advantage to achieve the urban water balance.

*4.3. Advantages of Water Circularity Indicator*

Monitoring and further improvement of urban water flows is the main motivation behind the formulation of WCI. For a given city with existing conditions, WCI can be computed which would be a starting value considering the existing application of 5Rs strategies. However, with development directed towards CE implementation in water sector the WCI value can be used for monitoring the improvements. The availability of such a simple scale indicator can help the utility managers to envision results and take appropriate initiatives. Following are some of the advantages of WCI, highlighting the role of WCI in the overall CE implementation in water sector.

- WCI provides valuable information through a simple numerical value.
- WCI captures the impact of all 4Rs i.e., reuse, recycle, reclamation and restoration to efficiently assess and monitor the CE in urban water sector.
- WCI value equals the sum of the fraction of water reused, recycled, reclaimed and restored when usage efficiency is 100%.
- The indicator can be used for policy implications to enhance water security at the desired scale. Comparison based on the indicator and its easy interpretation makes it useful for decision-makers and all the stakeholders involved in the CE implementation process.
- On a regional scale, benchmarking can be conducted to enhance the optimal utilization of water. Innovative techniques to achieve the benchmark targets can also be applied and their impacts can further be assessed.
- Continuous monitoring based on WCI values can create pressure on utility managers or authorities to maintain a sustainable water environment.

*4.4. Limitations and future scope of the study*

As discussed in the previous sections, it is evident that WCI acts as a holistic indicator to depict the current water situation in the concerned region. However, there exists certain limitations that need to be addressed along with the future scope of work are discussed as follows:

- Presently, WCI considers only water flows within the defined system boundary. However, to completely evaluate urban water systems, energy, nutrients and other material aspects also needs to be considered which can be incorporated in future studies.
- WCI gives equal weightage to reduce, reuse, recycle, reclamation, and restoration; however, each 'R' involves advantages and challenges in their implementation. Thus, there is a need to prioritize each 'R' based on its feasibility of application which is the limitation of this study. In further extension of this work, a framework can be developed to incorporate weights of each of the 5Rs strategy within WCI.
- In the current study, losses are considered to be 20% as per the CPHEEO norms which include human consumption losses, physical distribution losses, as well as evaporation losses during consumption. Such losses vary regionally based on actual consumption and imparts a limitation to this study. In future, appropriate quantification of real losses needs to be considered for the evaluation of contextual WCI values.

## 5. Conclusions

Global depletion of water resources has driven the research community to formulate numerous frameworks towards overall water management. The application of CE framework in the urban water sector can also help in urban water management. The concept of circularity allows for the diversification of flows without exhausting the available resources. An indicator called MCI proposed by EMF and Granta design assessing circularity of material, is modified in the current study to derive a novel indicator WCI. Following are the conclusions from this study:

- WCI is proposed to assess, monitor and improve the urban water flows. The purpose is to evaluate the implementation of 5R strategies along with the extent to which the application of each strategy can be extended.
- Utilizing the WCI values, an overall understanding of the urban water flows can be obtained and then benchmarking of each R for future water flows can be carried out. Further, interventions can be introduced to enhance the application of the 5Rs strategies leading to improvement in the water circularity within the city or region under consideration.
- Based on the extent of implementation, WCI gives a value ranging from 0 to 1.0. The lower value of WCI indicates lesser implementation of any of the combinations of 5R strategies and excessive consumption of virgin water resources. A higher value of WCI indicates that water is efficiently circulated within the system boundary and virgin water resource is appropriately utilized.
- In the three scenarios selected from 100 scenarios, the WCI (0.284) value in S24 is less with excessive virgin water consumption ($V = 96.66$ MLD). Whereas in S97, WCI (0.617) increases with a decrease in the virgin water consumption ($V = 44.34$ MLD). Similarly in S100, the WCI value (0.688) further increases, decreasing the virgin water ($V = 40.23$ MLD) consumption.
- Comparison of WCI with the other indicators focusing on urban water management provides useful insights favoring the application of WCI on a larger scale. Reuse and restoration strategies are not captured by CSR, WWPS and WWRtoWWT; reuse is not captured by WWTtoWW and restoration is not captured by IRR. Thus, other than WCI, none of the indicators capture all the R strategies that CE entails.
- Applying WCI in a city or region will also help to fulfill and monitor SDG 6 targets 6.3, 6.4, 6.5, 6.6 by incorporating 5Rs strategies to improve urban water goals. Also, SDG 12 targets 12.2 and 12.5 can be addressed by optimizing the consumption of water as a crucial natural resource.

Thus, the WCI can provide comprehensive results compared to all the existing indicators to achieve water circularity inside the city or region under consideration. The novelty of WCI lies in its easy interpretation for decision-makers across multiple domains. Policy recommendations can be formulated to achieve a particular value of WCI to enhance CE in the water sector and reduce virgin water consumption, ultimately leading to water conservation. The application of WCI can be recommended for the overall management, improvement and monitoring of water circularity in the city or region under consideration. Utilities or water management authorities can beneficially utilize the results from WCI to understand the situation of water flows in the concerned city or region. Further, the utilities or concerned authorities can set appropriate targets for WCI and then highlight the progress they have made over a period of time. The inclusion of energy and material aspects can be explored further to enhance the competency of WCI in future studies. Assigning weights to each of the 5Rs in future work can drastically increase the reliability of WCI. Loses can also be meticulously assessed for precise outcomes and intensive application of WCI in future work.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

Angelakis, A.N., Gikas, P., 2014. Water reuse: Overview of current practices and trends in the world with emphasis on EU states. Retrieved from:Water Util. J. 8, 67–78 Last accessed: 22nd July 2021 http://www.ewra.net/wuj/pdf/WUJ_2014_08_07.pdf.

Arora, M., Yeow, L.W., Cheah, L., Derrible, S., 2022. Assessing water circularity in cities: methodological framework with a case study. Resour. Conserv. Recycl. 178, 106042. https://doi.org/10.1016/j.resconrec.2021.106042.

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T., Deletic, A., 2014. A critical review of integrated urban water modelling - urban drainage and beyond. Environ. Model. Softw. 54, 88–107. https://doi.org/10.1016/j.envsoft.2013.12.018.

Behzadian, K., Kapelan, Z., 2015a. Modelling metabolism based performance of an urban water system using WaterMet2. Resour. Conserv. Recycl. 99, 84–99. https://doi.org/10.1016/j.resconrec.2015.03.015.

Behzadian, K., Kapelan, Z., 2015b. Advantages of integrated and sustainability based assessment for metabolism based strategic planning of urban water systems. Sci. Total Environ. 527–528, 220–231. https://doi.org/10.1016/j.scitotenv.2015.04.097.

Bouziotas, D., van Duuren, D., van Alphen, H.J., Frijns, J., Nikolopoulos, D., Makropoulos, C., 2019. Towards circular water neighborhoods: simulation-based decision support for integrated decentralized urban water systems. Water (Switzerland) 11. https://doi.org/10.3390/w11061227.

British Standard, BS 8001, 2017. Framework for implementing the principles of the circular economy in organizations. Guide. The British Standard Institution.

Brown, R.R., Keath, N., Wong, T.H.F., 2009. Urban water management in cities: historical, current and future regimes. Water Sci. Technol. 59, 847–855. https://doi.org/10.2166/wst.2009.029.

Butler, D., Davies, J.W., 2000. Urban Drainage. Taylor & Francis, Abingdon, UK https://doi.org/10.4324/9780203244883.

Central Public Health and Environmental Engineering Organization (CPHEEO), 1999. Manual on Water Supply and Treatment; Ministry of Urban Development, New Delhi. Retrieved from: http://cpheeo.gov.in/cms/manual-on-water-supply-and-treatment.php. (Accessed 22 July 2021).

Central Public Health and Environmental Engineering Organization (CPHEEO), 2013. Manual on Sewerage and Sewage Treatment, Part A: Engineering; Ministry of Urban Development, New Delhi in collaboration with Japan International Cooperation Agency, Japan: India, 2013. Retrieved from: http://cpheeo.gov.in/cms/manual-on-sewerage-and-sewage-treatment.php. (Accessed 22 July 2021).

Chu, J., Wang, J., Wang, C., 2015. A structure-efficiency based performance evaluation of the urban water cycle in northern China and its policy implications. Resour. Conserv. Recycl. 104, 1–11. https://doi.org/10.1016/j.resconrec.2015.09.011.

Collivignarelli, M.C., Todeschini, S., Abbà, A., Ricciardi, P., Carnevale Miino, M., Torretta, V., Rada, E.C., Conti, F., Cillari, G., Calatroni, S., Lumia, G., Bertanza, G., 2021. The performance evaluation of wastewater service: a protocol based on performance indicators applied to sewer systems and wastewater treatment plants. Environ. Technol. (United Kingdom), 1–18 https://doi.org/10.1080/09593330.2021.1922509.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498.

Cucchiella, F., D'Adamo, I., Gastaldi, M., Koh, S.L., Rosa, P., 2017. A comparison of environmental and energetic performance of european countries: a sustainability index. Renew. Sust. Energ. Rev. 78, 401–413. https://doi.org/10.1016/j.rser.2017.04.077.

Di Maio, F., Rem, P.C., 2015. A robust indicator for promoting circular economy through recycling. J. Environ. Prot. (Irvine, Calif) 6, 1095–1104. https://doi.org/10.1680/warm.2008.161.1.3.

Di Maio, F., Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: a market value approach. Resour. Conserv. Recycl. 122, 163–171. https://doi.org/10.1016/j.resconrec.2017.02.009.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196.

EMF, Granta Design, 2015. Circularity Indicators - An Approach to Measuring Circularity - Methodology. Retrieved from: https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Methodology_May2015.pdf. (Accessed 22 July 2021).

Falkenmark, M., Widstrand, C., 1992. Population and water resources: a delicate balance. Retrieved from:Popul. Bull. 47, 1–36 Last accessed: 22nd July 2021 https://www.ircwash.org/sites/default/files/276-92PO-10997.pdf.

Farooqui, T.A., Renouf, M.A., Kenway, S.J., 2016. A metabolism perspective on alternative urban water servicing options using water mass balance. Water Res. 106, 415–428. https://doi.org/10.1016/j.watres.2016.10.014.

Franklin-Johnson, E., Figge, F., Canning, L., 2016. Resource duration as a managerial indicator for circular economy performance. J. Clean. Prod. 133, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023.

Gandy, M., 2004. Rethinking urban metabolism: water, space and the modern city. City 8, 363–379. https://doi.org/10.1080/1360481042000313509.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Ghosh, R., Kansal, A., Venkatesh, G., 2019. Urban water security assessment using an integrated metabolism approach-case study of the National Capital Territory of Delhi in India. Resources 8, 1–15. https://doi.org/10.3390/resources8020062.

Gleason Espíndola, J.A., Cordova, F., Casiano Flores, C., 2018. The importance of urban rainwater harvesting in circular economy: the case of Guadalajara city. Manag. Res. Rev. 41, 533–553. https://doi.org/10.1108/MRR-02-2018-0064.

Hardy, M.J., Kuczera, G., Coombes, P.J., 2005. Integrated urban water cycle management: the UrbanCycle model. Water Sci. Technol. 52, 1–9. https://doi.org/10.2166/wst.2005.0276.

Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustain. Prod. Consum. 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018.

Hoekstra, A.Y., Buurman, J., Van Ginkel, K.C.H., 2018. Urban water security: a review. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaba52.

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., De Meester, S., 2017. Performance indicators for a circular economy: a case study on post-industrial plastic waste. Resour. Conserv. Recycl. 120, 46–54. https://doi.org/10.1016/j.resconrec.2017.01.013.

Jeong, S., Park, J., 2020. Evaluating urban water management using a water metabolism framework: a comparative analysis of three regions in Korea. Resour. Conserv. Recycl. 155, 104597. https://doi.org/10.1016/j.resconrec.2019.104597.

Jiménez, B., Asano, T., 2008. Water Reclamation and Reuse Around the World.

Kakwani, N.S., Kalbar, P.P., 2020. Review of circular economy in urban water sector: challenges and opportunities in India. J. Environ. Manag. 271, 111010. https://doi.org/10.1016/j.jenvman.2020.111010.

Kalmykova, Y., Sadagopan, M., Rosado, L., 2017. Circular economy - from review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 1–13. https://doi.org/10.1016/j.resconrec.2017.10.034.

Kennedy, C., Pincetl, S., Bunje, P., 2011. The study of urban metabolism and its applications to urban planning and design. Environ. Pollut. 159, 1965–1973. https://doi.org/10.1016/j.envpol.2010.10.022.

Kenway, S., Gregory, A., McMahon, J., 2011. Urban water mass balance analysis. J. Ind. Ecol. 15, 693–706. https://doi.org/10.1111/j.1530-9290.2011.00357.x.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2017.09.005.

Landa-Cansigno, O., Behzadian, K., Davila-Cano, D.I., Campos, L.C., 2020. Performance assessment of water reuse strategies using integrated framework of urban water metabolism and water-energy-pollution nexus. Environ. Sci. Pollut. Res. 27, 4582–4597. https://doi.org/10.1007/s11356-019-05465-8.

Makropoulos, T.C., Rozos, E., 2011. Managing the Complete Urban Water Cycle: The Urban Water Optioneering Tool, pp. 42–46 https://doi.org/10.13140/RG.2.1.3238.5682.

Makropoulos, C.K., Natsis, K., Liu, S., Mittas, K., Butler, D., 2008. Decision support for sustainable option selection in integrated urban water management. Environ. Model. Softw. 23, 1448–1460. https://doi.org/10.1016/j.envsoft.2008.04.010.

Marteleira, R., Pinto, G., Niza, S., 2014. Regional water flows - assessing opportunities for sustainable management. Resour. Conserv. Recycl. 82, 63–74. https://doi.org/10.1016/j.resconrec.2013.10.016.

Meng, X., Kenway, S., 2018. Analysing water sensitive urban design options. Water e-Journal 3, 1–18. https://doi.org/10.21139/wej.2018.037.

Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112.

Mhatre, P., Panchal, R., Singh, A., Bibyan, S., 2021. A systematic literature review on the circular economy initiatives in the European Union. Sustain. Prod. Consum. 26, 187–202. https://doi.org/10.1016/j.spc.2020.09.008.

Mitchell, V.G., Mein, R.G., McMahon, T.A., 2001. Modelling the urban water cycle. Environ. Model. Softw. 16, 615–629. https://doi.org/10.1016/S1364-8152(01)00029-9.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: what do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.

Moravej, M., Renouf, M.A., Lam, K.L., Kenway, S.J., Urich, C., 2021. Site-scale urban water mass balance assessment (SUWMBA) to quantify water performance of urban design-technology-environment configurations. Water Res. 188, 116477. https://doi.org/10.1016/j.watres.2020.116477.

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: a proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002.

Nika, C.E., Gusmaroli, L., Ghafourian, M., Atanasova, N., Buttiglieri, G., Katsou, E., 2020a. Nature-based solutions as enablers of circularity in water systems: a review on assessment methodologies, tools and indicators. Water Res. 183, 115988. https://doi.org/10.1016/j.watres.2020.115988.

Nika, C.E., Vasilaki, V., Expósito, A., Katsou, E., 2020b. Water cycle and circular economy: developing a circularity assessment framework for complex water systems. Water Res. 187, 116423. https://doi.org/10.1016/j.watres.2020.116423.

Nikolaou, I.E., Tsagarakis, K.P., 2021. An introduction to circular economy and sustainability: some existing lessons and future directions. Sustain. Prod. Consum. 28, 600–609. https://doi.org/10.1016/j.spc.2021.06.017.

Palme, U., Lundin, M., Tillman, A.M., Molander, S., 2005. Sustainable development indicators for wastewater systems - researchers and indicator users in a co-operative case study. Resour. Conserv. Recycl. 43, 293–311. https://doi.org/10.1016/j.resconrec.2004.06.006.

Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. J. Clean. Prod. 210, 200–216. https://doi.org/10.1016/j.jclepro.2018.10.357.

Park, J.Y., Chertow, M.R., 2014. Establishing and testing the "reuse potential" indicator for managing wastes as resources. J. Environ. Manag. 137, 45–53. https://doi.org/10.1016/j.jenvman.2013.11.053.

Parris, T.M., Kates, R.W., 2003. Characterizing and measuring sustainable development. Annu. Rev. Environ. Resour. 28, 559–586. https://doi.org/10.1146/annurev.energy.28.050302.105551.

Paul, R., Kenway, S., McIntosh, B., Mukheibir, P., 2018. Urban metabolism of Bangalore City: a water mass balance analysis. J. Ind. Ecol. 22, 1413–1424. https://doi.org/10.1111/jiec.12705.

Peña-Guzmán, C.A., Melgarejo, J., Prats, D., Torres, A., Martínez, S., 2017. Urban water cycle simulation/management models: a review. Water (Switzerland) 9, 1–29. https://doi.org/10.3390/w9040285.

Preisner, M., Smol, M., Horttanainen, M., Deviatkin, I., Havukainen, J., Klavins, M., Ozola-Davidane, R., Kruopienė, J., Szatkowska, B., Appels, L., Houtmeyers, S., Roosalu, K., 2022. Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector. J. Environ. Manag. 304. https://doi.org/10.1016/j.jenvman.2021.114261.

Renouf, M.A., Kenway, S.J., 2016. Evaluation approaches for advancing urban water goals. J. Ind. Ecol. 21, 995–1009. https://doi.org/10.1111/jiec.12456.

Renouf, M.A., Serrao-Neumann, S., Kenway, S.J., Morgan, E.A., Low Choy, D., 2017. Urban water metabolism indicators derived from a water mass balance – bridging the gap between visions and performance assessment of urban water resource management. Water Res. 122, 669–677. https://doi.org/10.1016/j.watres.2017.05.060.

Renouf, M.A., Kenway, S.J., Lam, K.L., Weber, T., Roux, E., Serrao-Neumann, S., Choy, D.L., Morgan, E.A., 2018. Understanding urban water performance at the city-region scale using an urban water metabolism evaluation framework. Water Res. 137, 395–406. https://doi.org/10.1016/j.watres.2018.01.070.

Rozos, E., Makropoulos, C., 2012. Assessing the combined benefits of water recycling technologies by modelling the total urban water cycle. Urban Water J. 9, 1–10. https://doi.org/10.1080/1573062X.2011.630096.

Rozos, E., Makropoulos, C., 2013. Source to tap urban water cycle modelling. Environ. Model. Softw. 41, 139–150. https://doi.org/10.1016/j.envsoft.2012.11.015.

Rozos, E., Tsoukalas, I., Ripis, K., Smeti, E., Makropoulos, C., 2017. Turning black into green: ecosystem services from treated wastewater. Desalin. Water Treat. 91, 198–205. https://doi.org/10.5004/dwt.2017.20926.

Sahely, H.R., Kennedy, C.A., 2007. Water use model for quantifying environmental and economic sustainability indicators. J. Water Resour. Plan. Manag. 133, 550–559. https://doi.org/10.1061/(ASCE)0733-9496(2007)133:6(550).

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.

Sassanelli, C., Rosa, P., Rocca, R., Terzi, S., 2019. Circular economy performance assessment methods: a systematic literature review. J. Clean. Prod. 229, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019.

Sgroi, M., Vagliasindi, F.G.A., Roccaro, P., 2018. Feasibility, sustainability and circular economy concepts in water reuse. Curr. Opin. Environ. Sci. Heal. 2, 20–25. https://doi.org/10.1016/j.coesh.2018.01.004.

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Indic. 9, 189–212. https://doi.org/10.1016/j.ecolind.2008.05.011.

Smol, M., Koneczna, R., 2021. Economic indicators in water and wastewater sector contributing to a circular economy (CE). Resources 10, 129. https://doi.org/10.3390/resources10120129.

Smol, M., Adam, C., Preisner, M., 2020. Circular economy model framework in the european water and wastewater sector. J. Mater. Cycles Waste Manag. 22, 682–697. https://doi.org/10.1007/s10163-019-00960-z.

Urich, C., Rauch, W., 2014. Modelling the urban water cycle as an integrated part of the city: a review. Water Sci. Technol. 70, 1857–1872. https://doi.org/10.2166/wst.2014.363.

van Leeuwen, C.J., Frijns, J., van Wezel, A., van de Ven, F.H.M., 2012. City blueprints: 24 indicators to assess the sustainability of the urban water cycle. Water Resour. Manag. 26, 2177–2197. https://doi.org/10.1007/s11269-012-0009-1.

van Schaik, M.O., Sucu, S., Cappon, H.J., Chen, W.S., Martinson, D.B., Ouelhadj, D., Rijnaarts, H.H.M., 2021. Mathematically formulated key performance indicators for design and evaluation of treatment trains for resource recovery from urban wastewater. vanJournal. Environ. Manag. 282, 111916. https://doi.org/10.1016/j.jenvman.2020.111916.

Venkatesh, G., Brattebø, H., Sægrov, S., Behzadian, K., Kapelan, Z., 2017. Metabolism-modelling approaches to long-term sustainability assessment of urban water services. Urban Water J. 14, 11–22. https://doi.org/10.1080/1573062X.2015.1057184.

Voulvoulis, N., 2018. Water reuse from a circular economy perspective and potential risks from an unregulated approach. Curr. Opin. Environ. Sci. Heal. 2, 32–45. https://doi.org/10.1016/j.coesh.2018.01.005.

Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renew. Sust. Energ. Rev. 68, 825–833. https://doi.org/10.1016/j.rser.2016.09.123.

WRI (Water Resources Institute), 2019. Aqueduct Water Risk Atlas. Retrieved from: https://www.wri.org/news/release-updated-global-water-risk-atlas-reveals-top-water-stressed-countries-and-states. (Accessed 30 April 2021).

Zaman, A.U., Lehmann, S., 2013. The zero waste index: a performance measurement tool for waste management systems in a "zero waste city". J. Clean. Prod. 50, 123–132. https://doi.org/10.1016/j.jclepro.2012.11.041.

Zhu, D., Chang, Y.J., 2020. Urban water security assessment in the context of sustainability and urban water management transitions: an empirical study in Shanghai. J. Clean. Prod. 275, 122968. https://doi.org/10.1016/j.jclepro.2020.122968.