Resources, Conservation & Recycling 178 (2022) 106042

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Assessing water circularity in cities: Methodological framework with a case study

Mohit Arora [a,b,*], Lih Wei Yeow [c], Lynette Cheah [c], Sybil Derrible [d]

[a] *School of Engineering, The University of Edinburgh, King's Buildings, Sanderson Building, Edinburgh, EH9 3FB, United Kingdom*
[b] *Department of Civil and Environmental Engineering, Imperial College London, Skempton Building, London, SW7 2AZ, United Kingdom*
[c] *Engineering Systems and Design, Singapore University of Technology and Design, Singapore*
[d] *Department of Civil, Materials, and Environmental Engineering, University of Illinois at Chicago, IL, United States*

ARTICLE INFO

Keywords:
Water metabolism
Urban water management
Circularity indicators
Circular economy
Water policy
Industrial ecology

ABSTRACT

With significant efforts made to consider water reuse in cities, a robust and replicable framework is needed to quantify the degree of urban water circularity and its impacts from a systems perspective. A quantitative urban water circularity framework can benchmark the progress and compare the impacts of water circularity policies across cities. In that pursuit, we bring together concepts of resource circularity and material flow analysis (MFA) to develop a demand- and discharge-driven water circularity assessment framework for cities. The framework integrates anthropogenic water flow data based on the water demand in an urban system and treated wastewater discharge for primary water demand substitution. Leveraging the water mass balance, we apply the framework in evaluating the state of water circularity in Singapore from 2015 to 2019. Overall, water circularity has been steadily increasing, with 24.9% of total water demand fulfilled by secondary flows in 2019, potentially reaching 39.6% at maximum water recycling capacity. Finally, we discuss the wider implications of water circularity assessments for energy, the environment, and urban water infrastructure and policy. Overall, this study provides a quantitative tool to assess the scale of water circularity within engineered urban water infrastructure and its application to develop macro-level water systems planning and policy insights.

1. Introduction

Over four billion people across the globe face severe water scarcity for at least a month every year (Mekonnen and Hoekstra, 2016). The situation is further complexed by the fact that over two billion people live in countries experiencing high water stress (UN Water, 2020). The circular economy (CE) movement holds potential to partially address this issue as it emphasizes more efficient use of (by-) products and end-of-life resources. Even though several qualitative propositions for water circularity exist today (EMF, 2018), circularity efforts have not been quantitatively assessed for their overall impact on a city's water consumption and its wastewater system (Abu-Ghunmi et al., 2016; Sgroi et al., 2018; Voulvoulis, 2018). With increasing costs of sourcing, treatment, and distribution of drinking water, and collection of wastewater (Derrible, 2018, 2019), metrics should be developed to estimate the benefits of water circularity. Renouf and Kenway (2017) highlighted *the limited quantification of "urban water performance" at the macro urban scale (whole of city) to monitor progress towards established urban water goals*. In that pursuit, cities would benefit from a system-wide quantitative assessment of water circularity. This study, thus, combines the existing paradigms of material circularity assessment methods developed for global (Haas et al., 2015, 2020) and national scales (Mayer et al., 2019) with the urban water metabolism evaluation framework proposed by Farooqui et al. (2016) to develop a city-level water demand and discharge driven circularity assessment framework.

It is important to highlight that water systems are inherently circular through the natural water cycle, in the same way that "biomass waste products re-enter the biosphere and are available for ecological cycles" (Haas et al., 2015, 2020). Nevertheless, spatiotemporal variations in both the intensity of precipitation and the location of demand can lead to water scarcity. Thus, this study focuses on anthropogenic water cycle in an urban system, which includes all human-managed water flows, and

---

* Corresponding Author: Mohit Arora, Department of Civil and Environmental Engineering, Imperial College London, Skempton Building, South Kensington Campus, London, United Kingdom; Institute for Infrastructure and Environment, University of Edinburgh, Kings Buildings, Sanderson Building, Edinburgh, EH9 3FB, United Kingdom.

E-mail addresses: marora@ed.ac.uk, m.arora@imperial.ac.uk, arora_mohit@mymail.sutd.edu.sg (M. Arora).

https://doi.org/10.1016/j.resconrec.2021.106042
Received 24 August 2021; Received in revised form 25 October 2021; Accepted 8 November 2021

is to be differentiated from circularity in the natural water cycle.

The remainder of this article is as follows: the next section provides a review of past efforts on water mass balance and their applicability to assess urban water circularity. This section is followed by the proposed methodological framework and circularity indicators that can be applied at urban scale assessment. This framework is applied to evaluate the water system of a case city, Singapore, detailing datasets to support the analysis. Subsequently, the results of the circularity assessment are reported. Finally, we discuss the implications on urban water circularity and water policy.

2. Literature review

In studies conducting Economy-wide Material Flow Analysis (EW-MFA), water flows are presented separately from other material flows as water flows are typically an order of magnitude greater by mass (Derrible et al., 2020; Eurostat, 2001; Krausmann et al., 2017). The MFA-based approach has advanced to become one of the main ways of assessing global (Haas et al., 2015, 2020) as well as national material circularity (Arora et al., 2019; Jacobi et al., 2018; Mayer et al., 2019) and has been recommended for assessing water circularity (Nika et al., 2020). However, an MFA-based assessment of city-level water circularity has not yet been defined. A primary characteristic of typical MFA studies can be stock accumulation due to the longer lifetime of materials such as steel, concrete etc. (Arora et al., 2019; Derrible et al., 2020) . However, representation of the flows of water and wastewater may not feature such stock characteristic given little residence time in the circulation system, distinguishing it from material flows. In addition, getting reliable data for water and wastewater quantities can be challenging due to diversified sourcing, losses, and leakage.

In precedent studies, water flows are typically reported in the form of water supply and wastewater, such as in Kennedy et al. (2007) that compared these flows for various cities. While water flows have been studied and represented across cities and territories, much less work has examined water flows from a circularity perspective, largely because few water reuse programs exist in the world (See Section S1, SI-1). An exception to this was in a study of the urban metabolism of Los Angeles County (Ngo and Pataki, 2008), where water recycling in the form of irrigation and groundwater reinjection was reported to have contributed “less than 5% of total consumption” in 1990 and 2000. In another study of a proposed urban development in Ripley Valley, Australia, water flows were analyzed in various scenarios such as gray- and used water recycling (Farooqui et al., 2016). The authors also put forth several metabolism indicators for water flows, including an “internal recycling ratio”, which was defined as the ratio between the “volume of water recycled internally” and the “total volume supplied to meet demand”. However, this work assumes several scenarios of wastewater recycling and reuse to showcase the potential of water circularity.

Further, Kenway et al. (2011a) formalized a systematic mass-balance framework that included both natural and anthropogenic flows and proceeded to apply this framework on various cities and territories in Australia. Kennedy (2012) also provided equations for water flows and extended the scope to include urban aquifers. Water flows have also been studied for Amsterdam in 2012 (Voskamp et al., 2017), Bangalore in 2013 (Paul et al., 2018) and Cape Town in 2014 (Currie et al., 2017). In the case of Amsterdam, water flows were analyzed looking at the quantity of raw and treated water imported for producing drinking (potable) water, and the amount of groundwater infiltration into the sewer. In the case of Bangalore, the accounting framework of Kenway et al. (2011a) was extended to include system losses and decentralized surface water supplies provided by private water retailers. In the case of Cape Town, rainfall and dam levels were of special focus as virtually all of the city’s water is sourced from rivers and dams which have been under stress from prolonged drought during the period from 2015 to 2017.

Existing water metabolism frameworks, thus, have been previously applied to hypothetical scenarios or to cities where the volume of recycled water is negligible with respect to the overall water system, focusing predominantly on mass balance without proper focus on circularity assessments. Hence, there is a need to extend the existing water accounting models and establish a quantitative framework for urban water circularity assessment, especially for cities that are considering water recycling practices. Such water circularity frameworks can leverage upon urban metabolism studies and recent advancements in the circular economy assessments.

Specifically, this study develops an urban water demand and discharge-driven quantitative circularity assessment framework that can be applied to different urban contexts. Further, the framework is applied to a case study of urban water systems in Singapore, a city which has developed elaborate policy and practice for reuse-driven water circularity. This framework can be applied to water-constrained cities and/or urban systems with some efforts on gathering water flow datasets either through government data or with typical bottom-up water accounting (Derrible et al., 2020). We further estimate the maximum potential water circularity that may be achievable for the case city and discuss the implications of improved circularity rates on infrastructural policies and energy footprints. This research facilitates the ongoing global efforts for anthropogenic/engineering water circularity through a quantitative substance flow and circularity analysis.

3. Methodology

3.1. Framework

In general, urban water demand is met by a variety of primary sources that may include groundwater, surface water, and seawater. Depending on local water governance and infrastructure, water supply may have centralized, decentralized, or hybrid distribution mechanisms for industrial, commercial, and domestic consumption (Hoffmann et al., 2020). To develop a robust and replicable water circularity assessment framework, water demand and discharge can be aggregated at the city-level to absorb the complexities of sourcing, distribution systems, and diversity of socio-technical consideration across urban water systems. In this pursuit, we organize water flows in an urban system based on the anthropogenic water cycle, where water is sourced from various sources to meet the urban water demand, and it is discharged as wastewater of varied quality into the natural water cycle. Wastewater discharge from various sources across the city can be centrally collected for recycling and then further used to substitute primary water demand. It is important to highlight that the overall water cycle in an urban region includes natural flows that complement anthropogenic water cycle in water circularity. Additionally, there are material and energy interlinkages with anthropogenic water cycle responsible for indirect water footprint of products and services that cities supply. However, from an engineered water systems perspective, urban demand and discharge is managed and controlled by anthropogenic actors and thus we focus primarily on anthropogenic (engineered/human managed) water infrastructure for circularity assessment at a city scale. This approach is intended to help develop water planning and policy interventions at a higher level of urban water management strategy.

To provide a representative understanding of different water flows, Fig. 1 shows a generic urban water system based on water mass balance (Farooqui et al., 2016; Kenway et al., 2011a; Paul et al., 2018) and proposed circularity assessment framework with indicators. Fig. 1a provides an overview of the urban water system from the water flow perspective and includes both natural and anthropogenic flows with inclusion of Managed Aquifer Recharge (MAR) (Page et al., 2018). MAR strategies like injection wells and infiltration basins can play a key role in sustainable urban groundwater management and are being adopted by many cities. Natural infiltration inhibited by impervious urban surfaces together with over-extraction of groundwater can contribute to undesirable ecological consequences like land subsidence (Chaussard

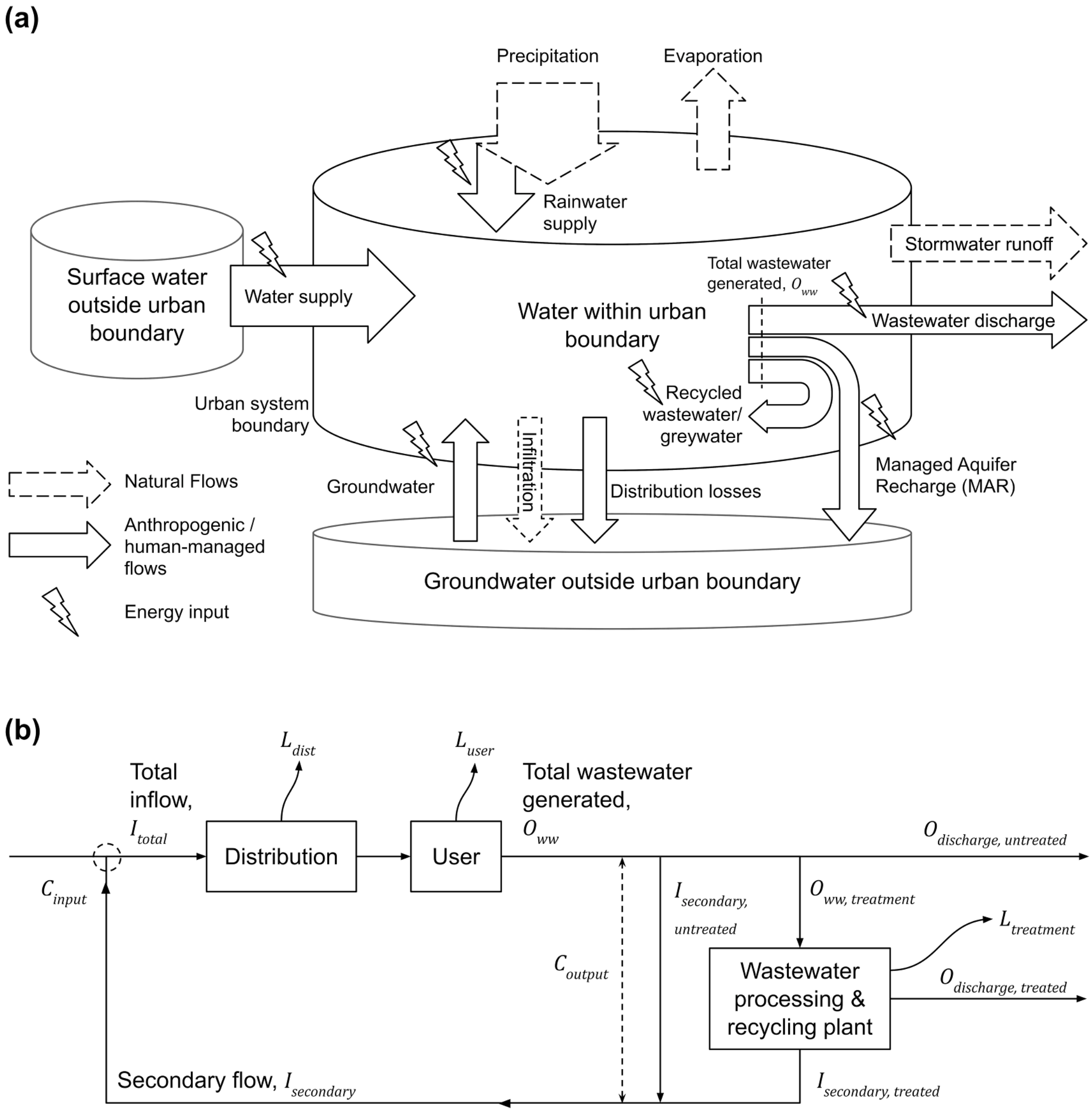

Fig. 1. Water circularity assessment framework consisting of (a) an urban water flow diagram including natural and anthropogenic flows and (b) simplified schematic diagram with consolidated water flows necessary for calculating anthropogenic water circularity.

et al., 2013; Xu et al., 2012). Fig. 1a also depicts natural flows such as precipitation, evaporation, infiltration and stormwater discharge. Of all precipitation falling in the urban boundary, a portion could be captured by human-managed rainwater harvesting systems, while the remainder could leave the urban boundary as stormwater runoff or infiltrated into the groundwater. Water could also leave the urban area by evaporation from exposed water bodies, outdoor water features, washing, or urban vegetation. Fig. 1b provides consolidated anthropogenic water flows into and out of an urban system required for calculating water circularity along with water losses across the system. The terms represent annual volumes, usually expressed in cubic meters (m^3) per year. The total water input (I_{total}) is defined as the total volume of water required to meet urban water demand of all users within a city where users represent all industrial and societal consumers within a city that use water for various end-usages. This quantity includes water drawn from various primary and secondary sources. Primary sources include water supplies from outside of the urban boundary, groundwater extraction, or harvested rainwater, while secondary sources include recycled gray- or wastewater. Urban demand includes potable and non-potable uses, and additional water required to meet demand with distribution losses.

Conversely, the total wastewater generated (O_{ww}) by the users is separated into three components: (a) the volume of untreated wastewater used to meet specialized urban water demand ($I_{secondary,\ untreated}$), (b) the volume of wastewater sent to a wastewater treatment or recycling plant ($O_{ww,\ treatment}$) and (c) the volume of wastewater directly discharged without treatment ($O_{discharge,\ untreated}$). From the wastewater treatment plant, a portion of treated wastewater is discharged ($O_{discharge,\ treated}$) while another portion is directed for reuse ($I_{secondary,\ treated}$). In this study, discharge refers to wastewater flows leaving the urban boundary, such as effluent flowing into rivers and seas.

Finally, secondary flow ($I_{secondary}$) is the total volume of water that is treated to a level suitable for use and forms part of total water demand. The total secondary flow is the sum of secondary flows from treated ($I_{secondary,\ treated}$) and untreated ($I_{secondary,\ untreated}$) sources. One example of a treated secondary flow ($I_{secondary,\ treated}$) is potable water recycled at advanced treatment plants, while untreated secondary flows ($I_{secondary,\ untreated}$) refer to the direct, non-potable reuse of wastewater (e.g. gray water), such as the use of laundry effluent for toilet-flushing or irrigation. Secondary flows are separated into treated and untreated sources for accounting purposes, as treated secondary flows are likely to originate from centralized processing plants which measure input and output flows, while untreated flows are likely to occur in a decentralized manner with low data accessibility.

For circularity assessment, we define water circularity from the perspective of substitution of primary water demand and, thus, the fraction of wastewater that is treated to a water quality level and that can be reused to substitute primary water supply. The proposed framework defines water circularity based on primary water input and/or demand substitution and discharge reusability. Quantitatively, absolute water circularity can be expressed in terms of an input circularity rate (C_{input}) , which measures the proportion of water supplied from recycled water to meet urban water demand. Thus, input circularity rate represents the dependence of the urban water system on secondary flows for meeting primary demand.

As recycling efforts have been the key circularity measures in many cities, we extend the circularity measurement representation from the perspective of urban water discharge or outflow. This is inspired by the material circular economy concept of 'socioeconomic cycling' where both input and output socioeconomic cycling rates are tracked (Haas et al., 2020; Mayer et al., 2019).

To consider the proportion of wastewater discharge that is recycled to a quality level that can potentially substitute primary water demand, we define output circularity rate (C_{output}) as the fraction of treated wastewater out of total wastewater generated from an urban system. Output circularity highlights the extent of wastewater treatment in a city and the gap in achieving the total water circularity potential. Theoretically, the maximum water circularity potential in city is represented by the total generated wastewater that must be treated to a certain water quality level for reuse. Output circularity thus assumes that the water quality, after wastewater treatment, can be achieved to a level that is sufficient to comply with the quality requirements set for any application within the urban system. It is important to highlight that the water quality standards for different end-uses can vary significantly based on jurisdictions just as the wastewater discharge standards to natural water bodies. This point is also crucial for cities and/or jurisdictions where effluent discharge standards into water bodies and/or sea are lower than the water quality standards recommended for industrial or domestic water consumption.

Based on inflow substitution and outflows recycling perspective, we define two key indicators of input and output circularity (in percentages) for circularity assessment. As such, these two indicators can be defined in the following equations:

$$C_{input} = \frac{I_{secondary}}{I_{total}} \tag{1}$$

$$C_{output} = \frac{I_{secondary}}{O_{ww}} \tag{2}$$

Additionally, a wastewater treatment rate is defined as the proportion of wastewater generated that is sent for treatment:

$$R_{treatment} = \frac{O_{ww,\ treatment}}{O_{ww}} \tag{3}$$

Water losses from distribution (L_{dist}), usage (L_{user}), and treatment ($L_{treatment}$) are also shown in Fig. 1b, and the types of water losses listed are non-exhaustive. In practice, such losses should be quantified in accordance with the local context of a selected urban water system and will be necessary when calculating other key quantities when such data is unavailable. Furthermore, quantifying losses also play a key role in identifying the opportunities and pathways towards greater water circularity.

Since the key quantities required to calculate the water circularity rates are (a) the total water input (I_{total}), (b) volume of wastewater generated (O_{ww}), and (c) volume of water recycled and reused ($I_{secondary}$), it is reiterated that this study focuses primarily on the anthropogenic water cycle with little attention to natural flows such as precipitation, evaporation, and infiltration. While these are important flows in urban water systems, such as the role of precipitation and infiltration in rainwater/stormwater collection, their quantities do not affect the calculation of anthropogenic water circularity and recycling ratios. Further, this framework assumes that the residence time of water and wastewater in urban systems is less than a year such that the circulation completes without any water 'stock' developments via artificial storage and/or reservoirs. With availability of more granular data, it is however possible to perform circularity assessments at shorter time periods and analyze seasonality effects.

3.2. Case study of Singapore

To apply the framework developed in this study, we leverage the availability of urban water system data in Singapore. Singapore is a dense island city-state located one degree north of the equator in Southeast Asia. Despite receiving more than two meters of rainfall annually (weather.gov.sg, 2019), Singapore is considered to face absolute water scarcity. Its total renewable water resource (TRWR), known as the maximum theoretical amount of water actually available for a country at a given moment is reported to be 105.1 m^3 per year per capita, which is relatively low (FAO, 2014; 2019). Given its small size and lack of aquifers (Tortajada and Buurman, 2017), water catchment remains insufficient to meet local water demand. Singapore has developed four major sources of water (termed as the "four national taps"): (1) local water catchments, (2) imported water from the Johor River in Malaysia, (3) desalination of seawater, and (4) water reuse through advanced wastewater treatment named NEWater. NEWater is of high quality, surpassing the World Health Organization's (WHO) guidelines for drinking water quality (PUB, 2020) and its low level of organic substances attract industries requiring high water purity, such as wafer fabrication plants (PUB, 2021).

With 17 reservoirs, over two-thirds of Singapore's land area is considered as local water catchment area with long-term plans to increase it to 90% by 2060 (Irvine et al., 2014). Imported water from the Johor River is limited by a 1962 water agreement between the Singapore and the State of Johor, Malaysia. The agreement allows Singapore to draw up to 1.14 million m^3 of raw water from the Johor River per day, or 250 million imperial gallons per day (mgd) (Tortajada et al., 2013). In return, the State of Johor is entitled to purchase 2% of treated water, that is, 22,730 m^3 per day (5 mgd). With the local catchment area close to maximum utilization and considering that water agreements will eventually lapse, future increases in water demand can only be fulfilled with desalination and water reuse (See Section S2. SI-1).

Singapore's water and wastewater networks along with the availability of granular data make it an exceptional city to apply the proposed urban water circularity assessment framework. In contrast to combined sewers, stormwater and used water (i.e., sanitary wastewater) are collected in separate storm and sanitary sewer systems (Irvine et al., 2014), which channel stormwater to rivers and reservoirs, and used water to wastewater treatment plants (Tortajada et al., 2013). The water distribution network is robust, with "[no] illegal connections, and all water connections are metered" (Tortajada and Buurman, 2017). This water circularity case study is further facilitated by Singapore's central water management landscape, with the key actor being the national water agency, i.e., the Public Utilities Board (PUB).

3.3. Data and water flows for case city

Annual water flows in Singapore are analyzed over a five-year period from 2015 to 2019 (See SI-2). Data on annual water sales, the volume of used water treated ($O_{ww,\ treatment}$), and the percentage of distribution losses ($1 - \varepsilon_{dist}$) are obtained from the annual publication *Key Environmental Statistics* by the Ministry of the Environment and Water Resources (MEWR) (MEWR, 2021) and the Singapore Department of Statistics (Singstat, 2021b). It should be noted that before 2019, distribution losses were previously reported as unaccounted for potable water, which did not account for "all possible leaks" (MEWR, 2021). As such, distribution losses increased from 5 to 5.6% between 2015 and 2019, to 8.2% in 2019. Water sales data details the volume of water sold to users in four streams: potable water for domestic ($I_{pot,dom}$) and non-domestic use ($I_{pot,non\text{-}dom}$), NEWater sold to industries for direct non-potable use (DNU) ($I_{NEWater,\ ind}$), and industrial water (I_{ind}). In contrast to high-quality NEWater, industrial water refers to inexpensive and lower-quality treated wastewater solely for industrial use (Tortajada et al., 2013). The variable ε_{dist} represents the efficiency of the water distribution network to account for leakage and/or distribution losses. All quantities are in annual volumes (m^3 per year). In calculating the total volume of water required to meet urban water demand, the volume of water sold to users in all four streams are summed. This is then divided by the efficiency of the water distribution network, ε_{dist}. Thus, I_{total} is calculated according to Eq. (4) below:

$$I_{total} = \frac{1}{\varepsilon_{dist}} \times \left(I_{pot,dom} + I_{pot,non-dom} + I_{NEWater,\ ind} + I_{ind}\right) \tag{4}$$

In the Singapore context, secondary flows ($I_{secondary}$) consist of the volume of NEWater directly sold to industries ($I_{NEWater,\ ind}$) and NEWater added into human-managed reservoirs for indirect potable use (IPU) (I_{IPU}), as well as the sales of industrial water. This is given by Eq. (5):

$$I_{secondary} = I_{NEWater,\ ind} + I_{IPU} + I_{ind} \tag{5}$$

With the key quantities of total water input (I_{total}), total wastewater generated (O_{ww}) and secondary flows ($I_{secondary}$), the two circularity indicators defined in Eqs. (1) and (2) can be calculated. Further, we discuss the scenario of maximum wastewater treatment capacity utilization for NEWater generation using information about existing wastewater treatment facilities. This is expressed with an increase in NEWater added into reservoirs for IPU ($I_{IPU,\ \max}$) and thus a greater secondary flow ($I_{secondary,\ \max}$). At the maximum installed capacity for treated water that can potentially be used for primary water demand reduction, the circularity has been estimated as:

$$C_{input,\ max} = \frac{I_{secondary,\ max}}{I_{total}} \tag{6}$$

$$C_{output,\ max} = \frac{I_{secondary,\ max}}{O_{ww}} \tag{7}$$

In the data obtained over the study period, annual total water sales from all four streams were observed to be greater than the volume of used water treated. This implies that not all of the water sold to users is recovered by the sewerage system. Such user losses could be caused by evaporation or discharge to the environment without returning to the sewerage system. These user losses (L_{user}) are calculated with the equation below:

$$L_{user} = I_{pot,dom} + I_{pot,non-dom} + I_{NEWater,ind} + I_{ind} - O_{ww} \tag{8}$$

Losses from treating used water and recycling ($L_{treatment}$) were calculated using processing efficiencies reported in the literature, with further details available in the Supplementary Information (Section S3. SI-1).

4. Results and discussion

In 2019, the total amount of water sold in Singapore was 663.6 Mm^3, with the majority coming from potable water sales (500.2 Mm^3), and NEWater and industrial sales (163.4 Mm^3). Domestic users consumed 59.5% (297.6 Mm^3) of potable water sales while the remaining 40.5% (202.6 Mm^3) were non-domestic. The volume of used water treated was 577.6 Mm^3, which implies that 86 Mm^3 of water was lost at the user stage, including through evaporation, industrial transformation processes, and gardening. Since all wastewater generated is collected by the sewerage system for treatment, $O_{ww} = O_{ww,treatment}$, and $R_{treatment} = 1$. With a total population of 5.70 million persons in 2019 (Singstat, 2021a), the overall per capita water consumption was 116.3 m^3, and domestic potable water consumption per capita was 52.2 Mm^3, or 143.0 liters per person per day.

Fig. 2 shows water flows of Singapore in 2019. Indirect potable use (IPU) of NEWater to human-managed reservoirs is assumed to be 16.6 million cubic meters (Mm^3) per year (10 mgd) (Tan et al., 2009). Inflow contributed by non-recycled water sources (imports, reservoirs, and desalination) amounted to 542.9 Mm^3. That year, the volume discharged to sea after treatment was 324.3 Mm^3. Total system losses from distribution, users and treatment amounted to 218.6 Mm^3. The secondary flow of 180.0 Mm^3 accounted for 24.9% of total water sales (input circularity) and 31.2% of total wastewater generated (output circularity).

To develop an alternative scenario of maximum circularity (Fig. 3), the main source of recycled water (NEWater) is assumed to run at 95% of maximum capacity. This involves the five NEWater plants currently operating with a total production capacity of 282.1 Mm^3 per year (170 mgd). Excess NEWater produced that is not sold directly to end users is assumed to be pumped into reservoirs and thus contributes to IPU ($I_{IPU,\ max}$). The single industrial water plant is not assumed to run at 95% of maximum capacity as demand for industrial water is limited. In this scenario, both input and output circularity increase to 39.6% and 49.5% respectively.

Despite the change in how distribution losses were reported before 2019, input circularity grew slightly over the five-year period from 23.8% in 2015 to 24.9% in 2019 (Fig. 4). This is largely due to an increase in the proportion of NEWater and industrial water sales that grew from 149.8 Mm^3 in 2015 to 163.4 Mm^3 in 2019. Output circularity increased from 29.0% in 2015 to 31.2% in 2019, with a slight dip in 2016 due to increased water demand relative to secondary water sales. Under the maximum circularity scenario where NEWater plants are assumed to operate at 95% capacity and excess NEWater is added to reservoirs, input circularity would grow from 29.9% in 2015 to 39.6% in 2019. This is attributed to the completion of the fifth NEWater plant with a capacity of 83 Mm^3 per year (50 mgd) (Boh, 2020) and the upgrading of an existing plant by 5 Mm^3 per year (3 mgd) in 2017, which brought the total NEWater capacity from 194.1 Mm^3 per year (117 mgd) in 2015 to 282.1 Mm^3 per year (170 mgd) in 2019.

The immediate limits to higher water circularity are the NEWater processing capacities. In order to reuse all treated used water, which is currently discharged into the sea in 2019, the total NEWater capacity would have to increase by more than 50% from 282.1 Mm^3 per year (170 mgd) in 2019 to about 426.6 Mm^3 per year (257 mgd), arriving at a maximum input circularity of 58.5% at 2019 consumption levels. However, this increase in NEWater capacity pales in comparison to the 786.5 Mm^3 per year (473 mgd) required to meet 55% of the projected total water demand in 2060 (PUB, 2018a). To meet such targets, there is a need to continue infrastructural investments for increased NEWater capacity in future.

5. Discussion

Water circularity assessment framework presented in this study provides an ideal mechanism for city planners and urban policy makers to benchmark current state of urban water circularity, establish robust future circularity targets based on water availability and demand, and ensure appropriate interventions. Two key indicators developed in this study, primarily the input and output water circularity rate, are crucial to quantify the scale of water circularity from both urban water demand and wastewater treatment perspective. These indictors offer an opportunity to track progress of water circularity over time under various measures such as investments in infrastructure, policy intervention, and behavior-dependent consumption trends. Framework also allows comparative assessments across cities, offering a clear system boundary of engineered urban water system and thus circumvents the complex natural water cycle associated modeling for easier communication with decision makers and wider public.

From indicators perspective, both input circularity and output circularity provide important insights for the urban water system. Case

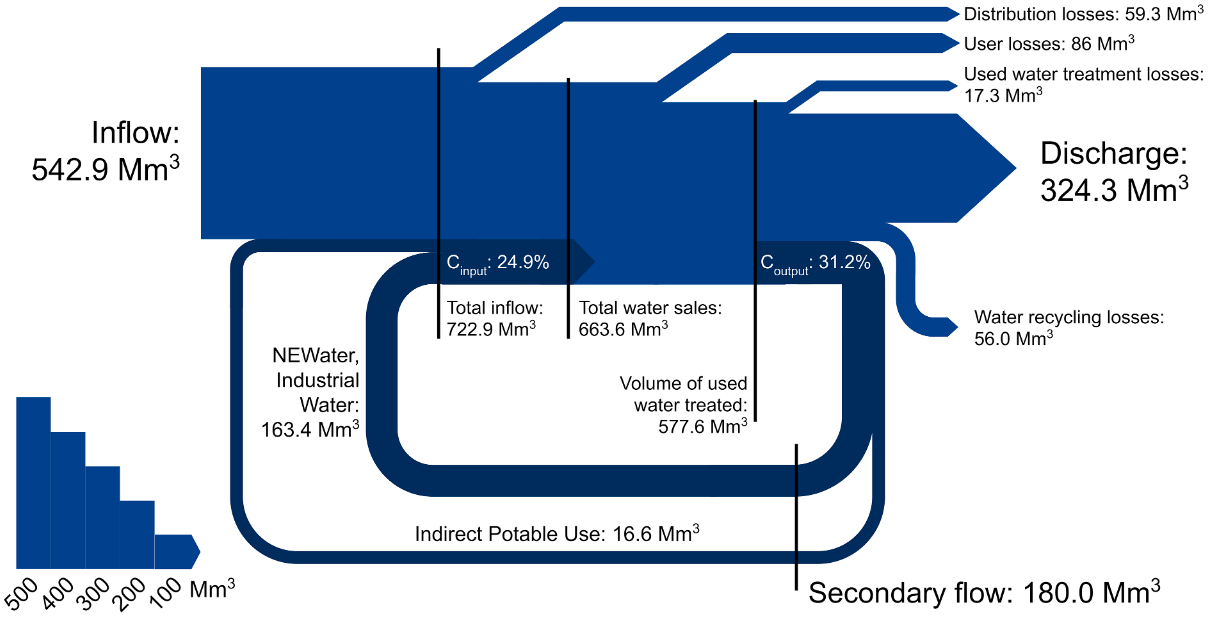

Fig. 2. Singapore's water flows and the scale of water circularity in 2019.

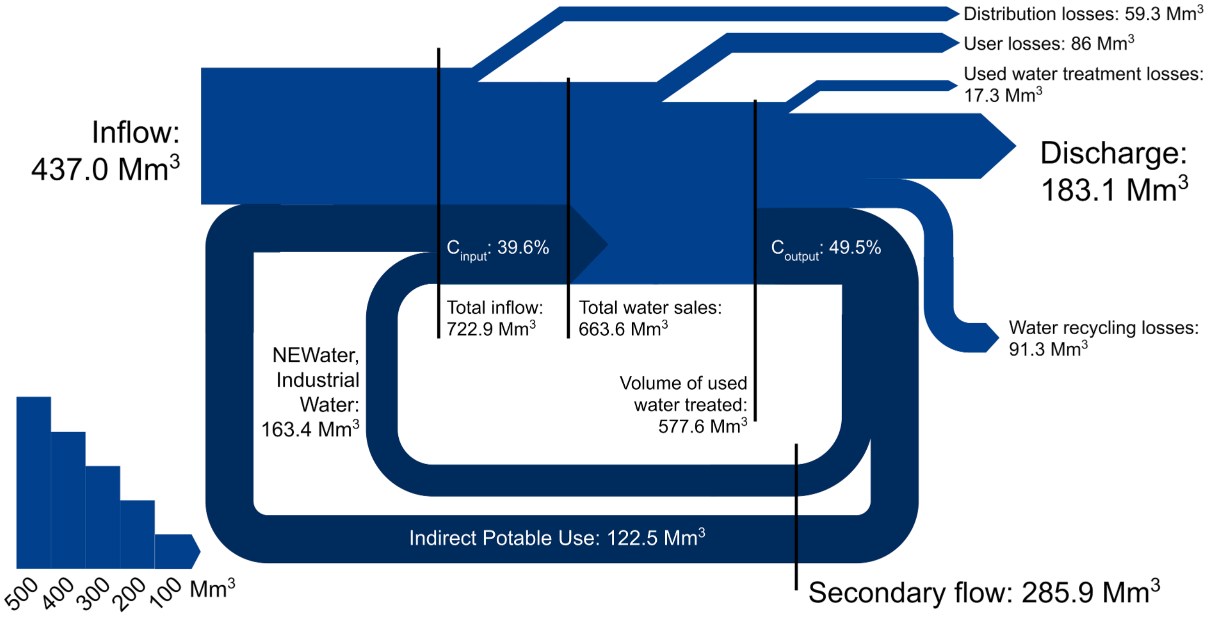

Fig. 3. Singapore's water flows and state of water circularity in an alternate scenario with maximum circularity driven by total wastewater treatment capacity utilization in 2019.

study for Singapore city highlights that the mass balanced approach used to create the urban water flow and circularity chart helps visualize the importance of input and output circularity estimation. Within circular economy debate, measuring waste outflows and their circularity has been the primary focus in academic studies which the input water circularity indicator tries to amend. An input water circularity rate helps identify the consumption based perspective of circularity by being a measure of primary water demand substitution. Output circularity rate follows the traditional waste generation-driven circularity perspective which highlights the scale of wastewater treated out of total wastewater generated from the city to a water quality level sufficient to meet industrial and/or urban water consumption standards. This indicator helps identify the scale of wastewater treatment and infrastructural capacities of the urban water system to treat and/or recycle water for urban consumption. Thus, having both input and output circularity indicators make the proposed framework balanced from both consumption and waste perspectives highlighting the pressure on water resources as well as the opportunities for improved recycling and reuse. It is important, however, to consider the treatment capacity and performance state of existing urban infrastructure to deliver maximum water circularity. Given the legacy issues around water systems across cities where infrastructure continues to remain under poor conditions, achieving maximum operational capacities for improved circularity can be a bigger challenge from economic and environmental perspectives.

Overall, water circularity in the form of gray- or wastewater recycling both at the household and city-scale can provide a less energy-intensive and climate-resistant option for cities facing water scarcity when compared to other common measures like desalination. However,

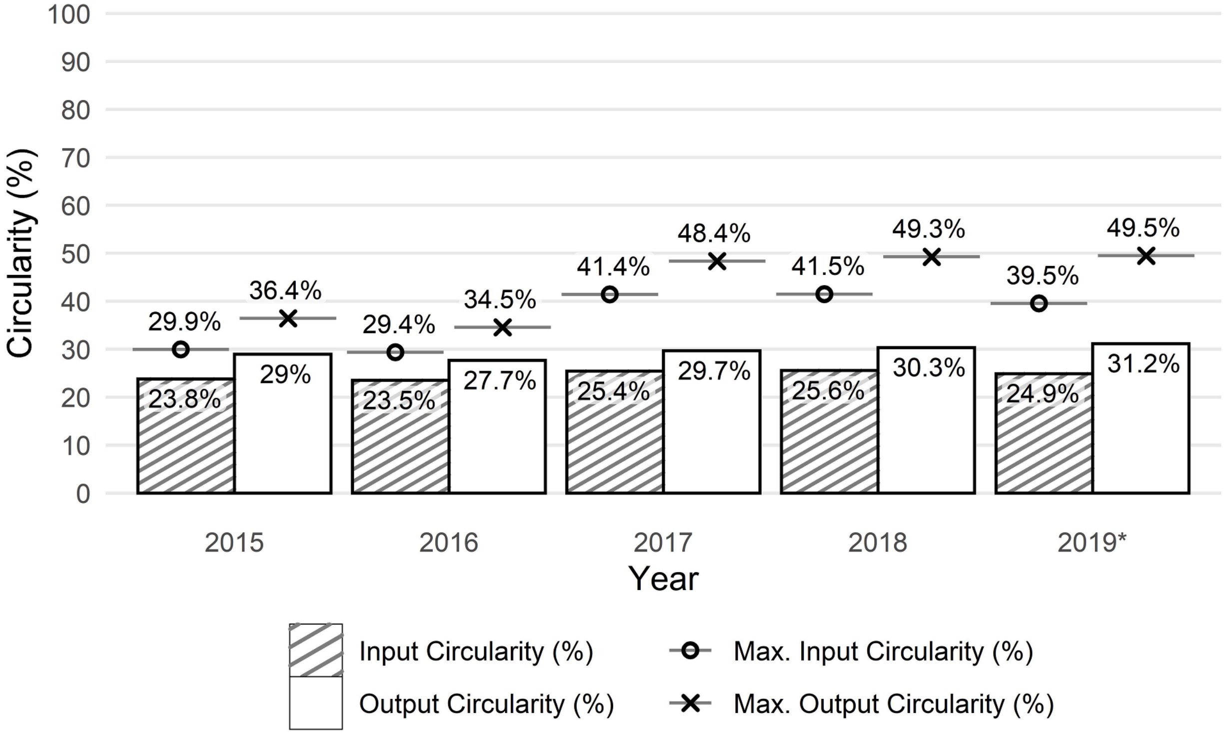

Fig. 4. Input and output water circularities for Singapore from 2015 to 2019. *The indicator for distribution losses was changed in 2019.

construction time, financing and social acceptance can be barriers to implementing water recycling programs and developing infrastructure to safely treat and distribute recycled water, especially for advanced water treatment technologies. But for the case of cities in arid climates that currently rely on energy-intensive desalination and groundwater abstraction for water, these investments are likely to be favorable. For example, wastewater treatment and reuse in six Saudi Arabian cities was estimated to reduce national electricity consumption by 2%, with savings arising from treatment and transportation (Kajenthira et al., 2012).

5.1. *Energy and economic implications of water circularity*

Energy inputs for operating urban water systems and recycling infrastructure imply that while achieving greater water circularity could address water scarcity, there may be negative environmental impacts in other realms. Increasing the production of recycled water (e.g. NEWater in Singapore) comes with both environmental and economic costs. For Singapore, it was reported in 2018 that the PUB's energy footprint was 1 TWh per year (PUB, 2018b), which was about 2% of total national electricity consumption of 49.6 TWh in 2017 (EMA, 2018). This is comparable to the global and US values where energy use for water was 1.7 – 2.7% of total global primary energy consumption (Chini and Stillwell, 2018; Liu et al., 2016). The energy required for producing potable water in Singapore are 0.2 kWh/m^3 from rainwater, 1 kWh/m^3 from used water via NEWater (including used water treatment) and 3.5 kWh/m^3 from sea water via desalination (Ng, 2016). As such, water reclamation plants in Singapore are currently 25% self-sufficient in energy by using biogas from sludge digestion (PUB, 2018b). Taking into account long-term plans such as reducing energy use for water processing and increasing process efficiency, Hsien et al. (2019) found that a unit of NEWater at the consumer will emit 31 – 35% more GHG emissions than a unit of tap water at the consumer, if the energy mix for Singapore has higher solar energy contribution in electricity production. Efforts in this direction have already started including large-scale floating solar farms that are being constructed and planned to (partially) power water treatment with renewable energy (Ng, 2021).

Still, achieving greater water circularity without additional environmental and energy costs is possible. Efforts on reduction in water losses from treatment, distribution and end-users would lead to decrease in the primary water demand as savings from water losses can be directed to meet the water consumption requirements. Thus, with a fixed level of production of recycled water, reduction in water losses will increase the input water circularity while reducing total energy use and environmental impacts as the proportion of water lost decreases in the overall system. For example, if the 86 Mm^3 of user losses in 2019 were eliminated and resulted in a corresponding decrease in potable water sales, input circularity would increase by 3.7 percentage points. Assuming potable water production from rainwater (0.2 kWh/m^3), the elimination of user losses would save at least 17.2 GWh of energy per year, or 1.7% of PUB's current energy footprint. Efforts in reducing water losses from treatment and distribution in Singapore are already underway. An array of sensors and analytical tools have been deployed to detect leaks in the water distribution network (PUB, 2016), while the PUB has set a goal of raising NEWater treatment efficiency from 75% to 90% (PUB, 2018a). Beyond this, future efforts should investigate reducing consumptive water use in addition to existing campaigns focused on overall water use reduction.

Maintaining such a circular system, however, also comes at an economic cost. Singapore's water system operational cost has increased from S$500 million to S$1.33 billion between 2000 and 2019 (PUB, 2019; Yuen-C, 2017). Capital cost investments for desalination, recycling, pipelines and pumping stations have been estimated to be over S $4 billion during 2017–21 (Today, 2017; Yuen-C, 2017). A potential cost recovery has been sought through water pricing, which include a water tariff (cost of water production and distribution), a water conservation tax (a policy measure to promote water efficiency and conservation) and a waterborne fee (cost of used water collection and treatment). The financial implications of infrastructural requirements for achieving greater circularity can be significant. For example, Singapore's latest investment to increase production of NEWater, comes at a cost of S$170 million for a wastewater treatment plant with a capacity of 83 Mm^3 (50 mgd) and an operating life of 25 years (Boh, 2020). This excludes the operational, maintenance and land costs.

5.2. Limitations

The framework developed for quantifying water circularity in urban areas is acknowledged to have certain limitations. Firstly, while the approach offers key metrics to portray circularity, the assessment on circularity cannot exclude accompanying discussion on water quality and the energy, environmental and economic impacts of various treatment technologies within the study context, as has been examined for the Singapore case. In addition, Singapore is a unique case in terms of data availability and governance of the water distribution network. Not all cities have ready data on water demand and discharge, formally metered connections, or full jurisdiction over the urban water system and, thus, transferability of proposed framework in this study depends on data availability for circularity estimates. Water quality is an important consideration for circularity efforts and has important implications for social acceptance of potable water reuse given various cultural and local contexts around cities. Moreover, the current study is conducted at a yearly timescale and does not account for stored water from year to year. Such an approach may not be valid for cities with large water stores such as dams or large aquifers where 'stocks' of water may influence the inflows and outflows. Further, the impact of alternative water distribution models (Derrible et al., 2021) and micro-scale efforts such as household-level water reuse or industrial demand reduction due to internal recycling could not be captured with a macro-scale assessment. Within the case study, the maximum circularity scenario assumes that NEWater plants operate close to their reported design capacity, which might not be true due to constraints in operation and maintenance. In addition, no significant modeling was undertaken to forecast future water consumption (e.g. as performed by Lee and Derrible, 2020) because primary consumption data for previous years was used, however, forecasting can be done for future projections as next step. Finally, while this study focuses heavily on anthropogenic water flows, arguments have been made for incorporating natural water cycles in achieving urban water circularity (Nika et al., 2020).

5.3. Achieving greater water circularity

The pathways towards environmentally sustainable water circularity lie in infrastructural investments, technological improvement and shifts to low carbon electricity grids. Coupling energy parity with raw water treatment and wastewater treatment and recycling together with low carbon electricity grids can reduce the environmental impacts of achieving greater water circularity. As mentioned by Hsien et al. (2019), addressing direct emissions from organic waste at wastewater treatment plants can have a significant reduction in the life cycle impacts of recycled water.

Additionally, advances in water circularity can be made when considering indirect water footprint of urban areas, such as the embodied water in products and food, which can overshadow real water flows by a large margin (Vanham, 2011). Water recovery from other waste streams not only increases water circularity but can offer co-benefits by reducing the moisture content in municipal solid waste in landfills, thus avoiding the generation of methane, a potent greenhouse gas (Mboowa et al., 2017).

The proposed water circularity framework allows planners to gain an overview of the circularity of the current water system, as well as locate the volume and stage at which water losses occur, and subsequently informing interventions to improve water circularity. Applying the framework at finer spatiotemporal scales and use cases could reveal further circularity opportunities, where the water used by one sector can be circulated by another sector. By facilitating coordinated water planning at a higher level, the proposed framework guides policy decisions towards urban and industrial symbiosis in water resources, which has been demonstrated to provide cost and water savings (Lu et al., 2020; Ramin et al., 2021).

One can argue that the natural water cycle tends to be inherently circular and thus the additional efforts on circularity may not be vital. This brings in the crucial difference between natural versus anthropogenic water cycles. The time duration and location for achieving water circularity are important considerations if water circularity were to address the challenge of societal water demand. The natural hydrological cycle – which includes precipitation, evaporation, freezing, melting and condensation – forms part of a global process of water circulation spanning large geographical and temporal scales (NASA, 2020). Hence, location-specific water demand requires anthropogenic interventions for timely circularity.

In water-scarce locations, the trade-off between lack of water and more-energy intensive water can eventually be settled based on meeting the existential water demand for communities, no matter the costs. In this context, it is important to highlight that the emission savings cannot always be the basis for greater circularity. Spatiotemporal lack of resources may often drive the circularity efforts fundamentally because the benchmark for life-saving resource availability takes precedence over energy considerations.

In addition to the magnitude of water flows, the issue of water quality should also play a more prominent role in discussions of water circularity. The inputs required to recycle water (in essence, raising water quality to the desired levels) should be weighed against the inputs required to obtain water of similar quality from conventional sources. For example, recycling greywater for non-potable use might require less inputs for treatment than if it were treated for potable use and would be low-hanging fruit for increasing water circularity. As a nutrient carrier, water and its circularity play an important role in critical nutrient recovery, such as phosphorus (Pearce and Chertow, 2017). Water circularity indicators that operate purely in the quantity domain should be augmented in the quality domain, like the proposed framework attempts to achieve in defining circularity based on water quality sufficient to match input water demand quality. Early attempts have been made in the field of material circularity, where indicators represent material quality with energy (Cullen, 2017; Steinmann et al., 2019). Extension of the current methodological framework may include the quality dimension of the water more explicitly in the circularity assessment to match the treatment level of the wastewater with its intended end-use, and identify nutrient recovery opportunities. Advancing the end-use disaggregation e.g. potable and non-potable circularity flows for separating water reuse flows will be useful for targeted interventions and estimates of energy costs and should be a part of the future advancements of circularity models.

6. Conclusion

Population growth and increasing urbanization have put pressures on water resources within urban areas and their surrounding environment. Meanwhile, the pursuit of a circular economy promises greater resource efficiency and sustainability. While water is already cycled through natural hydrologic processes, this cycle is increasingly brought under human control, driven by the scale of wastewater generation and advancements in water treatment technology due to increased pressure on natural/primary water sources. Furthermore, the benefits of achieving water circularity have significant implications on energy and material use. In light of significant efforts being made towards water circularity, this study fulfills the need for a robust and replicable framework for quantifying the degree of urban water circularity and the impact of additional circularity efforts from a systems perspective.

A quantitative urban water circularity framework, as proposed in this study, can greatly help in benchmarking the progress towards circularity. It can also facilitate a comparison across various cities implementing different water management policy measures. However, several challenges remain in developing a better quantitative understanding of water circularity in cities. One of the most prominent priority remains greater granularity of data which may allow spatio-temporal assessments of water circularity from a household to council or regional level during different time periods and/or seasonality. Localized insights for water circularity can help advance microscale interventions to deal with water shortage and scarcity and eventually contribute to societal resilience. Further expanding the concept of embodied and/or virtual water may also benefit the insights on 'lost' water volumes in delivering services and products to society. In the assessments of circularity, material and energy inputs and interlinks between water, materials and energy, such as the resources required to build and run advanced water recycling plants, are equally important to consider in the future (Cullen, 2017; Kenway et al., 2011b). Nonetheless, macro circularity assessment tools for water remain crucial for city planners and governments in dealing with supply chain vulnerability and security efforts under increasingly warmer climates in near future. With a more holistic understanding of the techno-economic and life cycle implications of water circularity under future water demands, decision makers can pick the most suitable measures for their local situations. Moving forward, circular economy may play a greater role in alleviating water scarcity, however, the investment policies must weigh in on the environmental and socioeconomic costs for an urban system.

CRediT authorship contribution statement

Mohit Arora: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Lih Wei Yeow:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Methodology. **Lynette Cheah:** Supervision, Conceptualization, Validation, Writing – review & editing. **Sybil Derrible:** Supervision, Conceptualization, Validation, Writing – review & editing.

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.

Acknowledgments

We thank Dr. Stefano Galleli and Dr. Nguyen Tan Thai Hung for a discussion on an earlier version of this research. Sybil Derrible would like to acknowledge the United States National Science Foundation (NSF) CAREER award under Grant No. 155173.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.106042.

References

Abu-Ghunmi, D., Abu-Ghunmi, L., Kayal, B., Bino, A., 2016. Circular economy and the opportunity cost of not 'closing the loop' of water industry: the case of Jordan. J. Clean. Prod. 131, 228–236.

Arora, M., Raspall, F., Cheah, L., Silva, A., 2019. Residential building material stocks and component-level circularity: the case of Singapore. J. Clean. Prod. 216, 239–248.

Boh, S. 2020 $170m fifth Newater plant launched, https://www.straitstimes.com/singapore/environment/170m-fifth-newater-plant-launched.

Chaussard, E., Amelung, F., Abidin, H., Hong, S.-.H, 2013. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. Remote Sens. Environ. 128, 150–161.

Chini, C.M., Stillwell, A.S, 2018. The State of U.S. urban water: data and the energy-water nexus. Water Resour. Res. 54 (3), 1796–1811.

Cullen, J.M., 2017. Circular economy: theoretical benchmark or perpetual motion machine? J. Ind. Ecol. 21 (3), 483–486.

Currie, P.K., Musango, J.K., May, N.D, 2017. Urban metabolism: a review with reference to Cape Town. Cities 70, 91–110.

Derrible, S., 2018. An approach to designing sustainable urban infrastructure. MRS Energy & Sustainability 5, E15.

Derrible, S., 2019. Urban Engineering for Sustainability. The MIT Press, Cambridge, MA.

Derrible, S., Cheah, L., Arora, M. and Yeow, L.W. (2020) Urban Informatics. Shi, W., Goodchild, M., Batty, M., Kwan, M.-P. and Zhang, A. (eds), Springer Nature Singapore.

Derrible, S., Truong, T.T.M., Pham, H.T., Nguyen, Q.H, 2021. Learning from Hanoi to imagine the future of water distribution. npj Urban Sustainability 1 (1), 9.

EMA 2018 Singapore energy statistics, https://www.ema.gov.sg/Singapore_Energy_Statistics.aspx.

EMF, 2018. Water and Circular Economy: White Paper. Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/assets/downloads/ce100/Water-and-Circular-Economy-White-paper-WIP-2018-04-13.pdf.

Eurostat, 2001. Economy-wide Material Flow Accounts and Balances With Derived Resource Use indicators: A methodological Guide. Office for Official Publications of the European Communities, Luxembourg.

FAO 2014 Water stress, http://www.fao.org/nr/water/aquastat/infographics/Stress_eng.pdf.

FAO 2019 Country Fact Sheet - Singapore, http://www.fao.org/nr/water/aquastat/countries_regions/index.stm.

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.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the World in 2005. J. Ind. Ecol. 19 (5), 765–777.

Haas, W., Krausmann, F., Wiedenhofer, D., Lauk, C., Mayer, A., 2020. Spaceship earth's odyssey to a circular economy - a century long perspective. Resour. Conserv. Recycl. 163, 105076.

Hoffmann, S., Feldmann, U., Bach, P.M., Binz, C., Farrelly, M., Frantzeskaki, N., Hiessl, H., Inauen, J., Larsen, T.A., Lienert, J., Londong, J., Lüthi, C., Maurer, M., Mitchell, C., Morgenroth, E., Nelson, K.L., Scholten, L., Truffer, B., Udert, K.M, 2020. A Research agenda for the future of urban water management: exploring the potential of nongrid, small-grid, and hybrid solutions. Environ. Sci. Technol. 54 (9), 5312–5322.

Hsien, C., Choong Low, J.S., Chan Fuchen, S., Han, T.W, 2019. Life cycle assessment of water supply in Singapore — a water-scarce urban city with multiple water sources. Resour. Conserv. Recycl. 151, 104476.

Irvine, K., Chua, L., Eikass, H.S, 2014. The four national taps of Singapore: a holistic approach to water resources management from drainage to drinking water. J. Water Manag. Model. 22, 1–11.

Jacobi, N., Haas, W., Wiedenhofer, D., Mayer, A., 2018. Providing an economy-wide monitoring framework for the circular economy in Austria: status quo and challenges. Resour. Conserv. Recycl. 137, 156–166.

Kajenthira, A., Siddiqi, A., Anadon, L.D, 2012. A new case for promoting wastewater reuse in Saudi Arabia: bringing energy into the water equation. J. Environ. Manage. 102, 184–192.

Kennedy, C. (2012) Sustainability Science: The Emerging Paradigm and the Urban Environment. Weinstein, M.P. and Turner, R.E. (eds), pp. 275–291, Springer New York, New York, NY.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The changing metabolism of cities. J. Ind. Ecol. 11 (2), 43–59.

Kenway, S., Gregory, A., McMahon, J., 2011a. Urban water mass balance analysis. J. Ind. Ecol. 15 (5), 693–706.

Kenway, S.J., Lant, P.A., Priestley, A., Daniels, P., 2011b. The connection between water and energy in cities: a review. Water Sci. Technol. 63 (9), 1983–1990.

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., Jackson, T., 2017. Material flow accounting: measuring global material use for sustainable development. Annu. Rev. Environ. Resour. 42 (1), 647–675.

Lee, D., Derrible, S., 2020. Predicting residential water demand with machine-based statistical learning. J. Water Resour. Plan. Manag. 146 (1), 04019067.

Liu, Y., Hejazi, M., Kyle, P., Kim, S.H., Davies, E., Miralles, D.G., Teuling, A.J., He, Y., Niyogi, D., 2016. Global and regional evaluation of energy for water. Environ. Sci. Technol. 50 (17), 9736–9745.

Lu, C., Wang, S., Wang, K., Gao, Y., Zhang, R., 2020. Uncovering the benefits of integrating industrial symbiosis and urban symbiosis targeting a resource-dependent city: a case study of Yongcheng, China. J. Clean. Prod. 255, 120210.

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., Blengini, G.A, 2019. Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. J. Ind. Ecol. 23 (1), 62–76.

Mboowa, D., Quereshi, S., Bhattacharjee, C., Tonny, K., Dutta, S., 2017. Qualitative determination of energy potential and methane generation from municipal solid waste (MSW) in Dhanbad (India). Energy 123, 386–391.

Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2 (2), e1500323.

MEWR 2021 Key environment statistics 2020. Available at https://www.mse.gov.sg/resources/key-environmental-statistics.pdf.

NASA 2020 Water cycle, https://science.nasa.gov/earth-science/oceanography/ocean-earth-system/ocean-water-cycle.

Ng, J.H., 2016. How Singapore will never go thirsty. The Straits Times. https://www.straitstimes.com/opinion/how-singapore-will-never-go-thirsty.

Ng, K.G. 2021 PUB eyes 2 large-scale floating solar farms at Lower Seletar and Pandan reservoirs, https://www.straitstimes.com/singapore/environment/pub-eyes-2-large-scale-floating-solar-farms-at-lower-seletar-and-pandan, Singapore.

Ngo, N.S., Pataki, D.E, 2008. The energy and mass balance of Los Angeles County. Urban Ecosyst. 11, 121–139.

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

Page, D., Bekele, E., Vanderzalm, J., Sidhu, J., 2018. Managed aquifer recharge (MAR) in sustainable urban water management. Water (Basel) 10 (3), 239.

Paul, R., Kenway, S., McIntosh, B., Mukheibir, P., 2018. Urban metabolism of Bangalore city: a water mass balance analysis. J. Ind. Ecol. 22 (6), 1413–1424.

Pearce, B.J., Chertow, M., 2017. Scenarios for achieving absolute reductions in phosphorus consumption in Singapore. J. Clean. Prod. 140, 1587–1601.

PUB 2018a Our water, our future, https://www.pub.gov.sg/Documents/PUBOurWaterOurFuture.pdf.

PUB 2018b PUB pushes the frontier of water technology to reach future energy and sludge reduction targets,https://www.pub.gov.sg/news/pressreleases/pubpushesthefrontierofwatertechnology.

PUB 2019 Annual Report, https://www.pub.gov.sg/annualreports/annualreport2019.pdf.

PUB 2020 NEWater Quality (Typical Values). https://www.pub.gov.sg/Documents/PUB_NEWater_Quality.pdf (ed), Singapore.

PUB 2021 NEWater Quality. https://www.pub.gov.sg/watersupply/waterquality/newater (ed), Singapore.

PUB, 2016. Managing the water distribution network with a Smart Water Grid. Smart Water 1 (1), 4. https://doi.org/10.1186/s40713-016-0004-4.

Ramin, E., Bestuzheva, K., Gargalo, C.L., Ramin, D., Schneider, C., Ramin, P., Flores-Alsina, X., Andersen, M.M., Gernaey, K.V, 2021. Incremental design of water symbiosis networks with prior knowledge: the case of an industrial park in Kenya. Sci. Total Environ. 751, 141706.

Renouf, M.A., Kenway, S.J, 2017. Evaluation approaches for advancing urban water goals. J. Ind. Ecol. 21 (4), 995–1009.

Sgroi, M., Vagliasindi, F.G.A., Roccaro, P., 2018. Feasibility, sustainability and circular economy concepts in water reuse. Curr. Opin. Environ. Sci. Health 2, 20–25.

Singstat 2021a M810001 - Indicators on population, annual, https://www.tablebuilder.singstat.gov.sg/publicfacing/createDataTable.action?refId=14912.

Singstat 2021b M890421 - Water Sales, Annual, https://www.tablebuilder.singstat.gov.sg/publicfacing/createDataTable.action?refId=14576.

Steinmann, Z.J.N., Huijbregts, M.A.J., Reijnders, L., 2019. How to define the quality of materials in a circular economy? Resour. Conserv. Recycl. 141, 362–363.

Tan, Y.S., Lee, T.J., Tan, K., 2009. Clean, Green and Blue: Singapore's Journey Towards Environmental and Water Sustainability. Institute of Southeast Asian Studies.

Today 2017 Operating cost of water system jumped S$0.8b in 15 years, https://www.todayonline.com/singapore/operating-cost-water-system-jumped-s08b-15-years.

Tortajada, C. and Buurman, J. 2017 Water policy in Singapore. Available at https://lkyspp.nus.edu.sg/gia/article/water-policy-in-singapore.

Tortajada, C., Joshi, Y., Biswas, A.K., 2013. The Singapore Water Story: Sustainable Development in an Urban City-state, Routledge. Taylor & Francis Group.

Vanham, D., 2011. How much water do we really use? A case study of the city state of Singapore. Water Supply 11 (2), 219–228.

Voskamp, I.M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J.P., Rijnaarts, H.H.M, 2017. Enhanced performance of the eurostat method for comprehensive assessment of urban metabolism: a material flow analysis of Amsterdam. J. Ind. Ecol. 21 (4), 887–902.

Voulvoulis, N., 2018. Water reuse from a circular economy perspective and potential risks from an unregulated approach. Curr. Opin. Environ. Sci. Health 2, 32–45.

Xu, Y.-.S., Ma, L., Du, Y.-.J., Shen, S.-.L, 2012. Analysis of urbanisation-induced land subsidence in Shanghai. Nat. Hazards 63 (2), 1255–1267.

UN Water, 2020. Water Facts- Scarcity, https://www.unwater.org/water-facts/scarcity/.

Yuen-C, T. 2017 Cost of supplying water has more than doubled: PUB, https://www.straitstimes.com/singapore/cost-of-supplying-water-has-more-than-doubled-pub.