Front. Environ. Sci. Eng. 2021, 15(1): 16
https://doi.org/10.1007/s11783-020-1308-z

REVIEW ARTICLE

Novel perspective for urban water resource management: *5R* generation

Lijie Zhou[1,2,3], Hongwu Wang[1,2], Zhiqiang Zhang[1,2], Jian Zhang[4], Hongbin Chen[5], Xuejun Bi[6], Xiaohu Dai[1,2], Siqing Xia (✉)[1,2], Lisa Alvarez-Cohen[7], Bruce E. Rittmann[8]

1 State Key Laboratory of Pollution Control and Resource Reuse, College of Environmental Science and Engineering, Tongji University, Shanghai 200092, China
2 Shanghai Institute of Pollution Control and Ecological Security, Shanghai 200092, China
3 College of Chemistry and Environmental Engineering, Shenzhen University, Shenzhen 518060, China
4 EnviroSystems Engineering and Technology Co., Ltd., Beijing 100083, China
5 National Engineering Research Center for Urban Pollution Control, Shanghai 200092, China
6 College of Environmental Science and Engineering, Qingdao University of Technology, Qingdao 266033, China
7 Department of Civil and Engineering, University of California, Berkeley, CA 94720-1500, USA
8 Biodesign Swette Center for Environmental Biotechnology, Arizona State University, Tempe, AZ 85287-5701, USA

HIGHLIGHTS

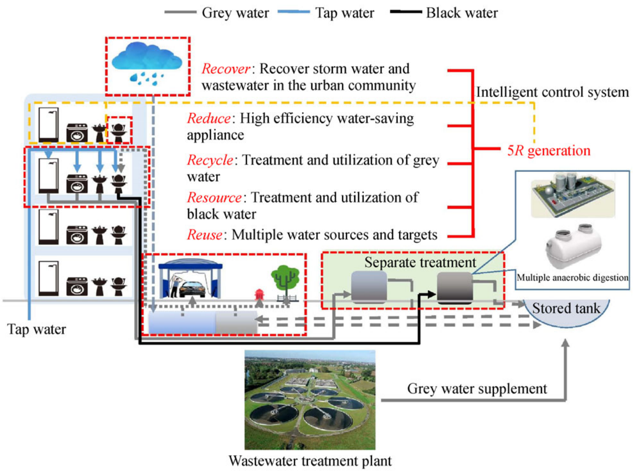
- *5R* (*Recover*, *Reduce*, *Recycle*, *Resource* and *Reuse*) approaches to manage urban water.
- *5R* harvests storm water, gray water and black water in several forms.
- *5R* offers promise for moving solutions for urban water scarcity in practice.

ARTICLE INFO

Article history:
Received 25 March 2020
Revised 30 June 2020
Accepted 3 July 2020
Available online 8 August 2020

Keywords:
5R generation
Recover
Reduce
Recycle
Resource
Reuse

GRAPHIC ABSTRACT



ABSTRACT

Demand for water is expanding with increases in population, particularly in urban areas in developing countries. Additionally, urban water system needs a novel perspective for upgradation with urbanization. This perspective presents a novel *5R* approach for managing urban water resources: *Recover* (*storm water*), *Reduce* (*toilet flushing water*), *Recycle* (*gray water*), *Resource* (*black water*), and *Reuse* (*advanced-treated wastewater*). The *5R* generation incorporates the latest ideas for harvesting storm water, gray water, and black water in its several forms. This paper has briefly demonstrated each *R* of *5R* generation for water treatment and reuse. China has the chance to upgrade its urban water systems according to *5R* principles. Already, a demonstration project of *5R* generation has been installed in Qingdao International Horticultural Exposition, and Dalian International Convention Center (China) has applied 5*R*, achieving over 70% water saving. The *5R* offers promise for moving solutions for urban water scarcity from “hoped for in the future” to “realistic today”.

✉ Corresponding author
E-mail: siqingxia@gmail.com, siqingxia@tongji.edu.cn

1 Introduction

1.1 The situation for water scarcity

At the center of social and economic development, water is vital for energy generation, agriculture, industry, environmental management, and cultural development (Kummu et al., 2010). However, the World Bank points out that ~4.5 billion people lack sanitation services and ~2.1 billion people lack clean drinking water. The World Economic Forum's Global Risks Report 2017 states that water scarcity is becoming the largest global risk, due in part to climate change, which will lead to more intense droughts, floods, glacial melting, and unpredictable precipitation. Improving living standards, changing consumption patterns, and irrigated agriculture expansion also are driving forces for water scarcity (Vörösmarty et al., 2000; Ercin and Hoekstra, 2014; Holmatov et al., 2017; Jiang et al., 2019). The World Bank estimates that current trends in population growth, coupled to current water-management practices, will lead globally to a 40% water shortfall of demand versus supply by 2030. Moreover, industrialization is an import part of urbanization with a large amount of water demand, leading to water scarcity. In São Paulo (Brazil) of urbanization, industrialization consumed over 13% total water utilization, and its water demand is increasing (Paiva et al., 2020). Industrialization also discharges highly hazardous wastewater, such as 3.4 × 10^7 t of industrial wastewater discharging into the surface water bodies in Zhangjiakou City (China) (Dai et al., 2019).

The uneven distribution of water resources accentuates the problems of worldwide water scarcity. For example, Fig. 1 shows the distribution of water availability. Mekonnen and Hoekstra (2016) reported that annual water-stock availability of China is only 2140 m^3/person, while Canada has up to 103000 m^3/person. They also shows the calculated annual scarcity of blue-water (fresh surface water + groundwater) at 30 × 30 arc-min resolution; severe water scarcity (deep red color) prevails in locations with either high population density (e.g., in North Africa, Australia, Arabian peninsula, London, San Francisco Bay, and Hainan island), the presence of intensely irrigated agriculture (Great Plains in the United States), or both (India, eastern China, and the Nile delta).

Large water consumption relative to water availability results in decreased river flows (especially during dry periods), declining lake levels, and declines in groundwater levels; these impacts probably cause environmental issue, like land subsidence, ground fissures, seawater intrusion, the deterioration of the ecological environment (Kim et al., 2018). Therefore, researchers and policy makers are focusing on water management to find essential solutions for water scarcity (Dunn et al., 2018; Jensen and Wu, 2018). Alongside the very large water demands from agriculture and power generation, urbanization is a major contributor to the seriousness of water shortages, particularly in cities.

Urbanization is one of the most significant trends of the 21st century, and 2.6 billion additional urban dwellers are expected by 2050 (Mcdonald et al., 2014). The Department of Economic & Social Affairs of the United Nations reports that Tokyo, New Delhi, Shanghai, Mexico City, and São Paulo each will exceed 22 million inhabitants by 2030, and the world is projected to have 43 megacities with more than 10 million inhabitants, most of them in

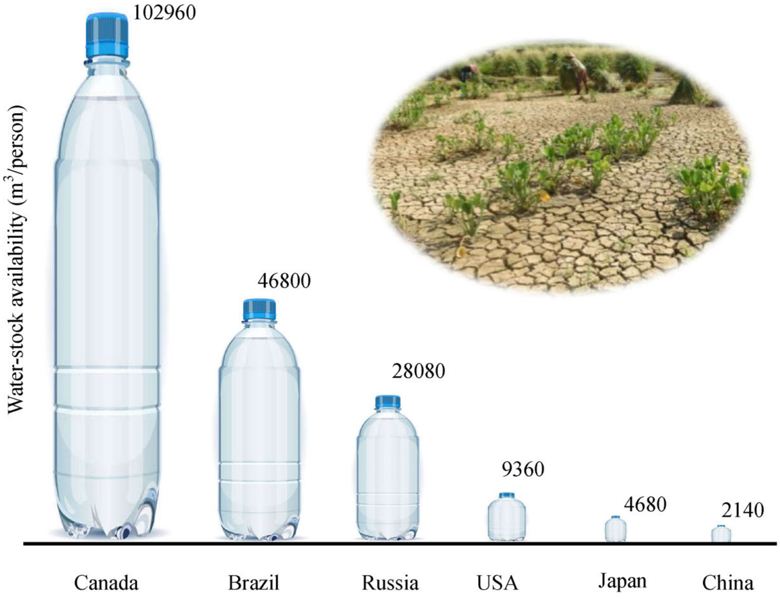


Fig. 1 Distribution of water availability (bottle size representing annual water stock m^3/person).

developing regions, by 2030. The increasing freshwater demand from greater population for urbanization has become a more important reason for water scarcity in many countries, especially in China and Mexico (Jiang, 2009; Eakin et al., 2016), and urban water scarcity is a serious threat to the sustainability of human society (Rockström et al., 2015; Hong et al., 2018; Wei et al., 2018).

1.2 Upgradation of urban water system

With higher and higher effluent quality requirement, urbane water system needs an upgradation for multiple utilization, and early project of water reclamation and reuse in Singapore was failed because of underdeveloped technology (Kog, 2020). Thus, new technologies of water and wastewater treatment are started to applied in wastewater treatment plants, like membrane separation (Song et al., 2018). However, membrane separation would improve advanced water treatment, but energy and cost inhibit wide application of membrane technology (Judd, 2017). Recently, management of membrane separation would be considered as one of effective application control, beside new membrane material development (Krzeminski et al., 2017; Song et al., 2018; Qu et al., 2019).

Urban water system, especially sustainable urban water management, have been developed and upgraded for over decades (Marlow et al., 2013; Lu et al., 2020). Unstructured system with some storm sewers in large cities serviced on basic service in urban water system, and water pipes building-up is applied for secure supply of wholesome water. Water pipes and sewers in urban water system is upgraded for public health and drainage in large cities. Therefore, urban water system needs a novel perspective for upgradation with urbanization.

1.3 Managing urban water

The red line in Fig. 2(a) illustrates the typical way that urban water is managed today. Taking in water from a water source, a water-treatment plant treats the water to potable quality, and the potable water is transported to customers via a distribution pipe network. A prime customer, and one that sets the quality standard, is the household. In a traditional household, showering, laundry, cooking, drinking, toilet flushing, and gardening are the major water consuming activities. Showering, laundry, and cooking plus drinking normally comprise about 18%, 17%, and 25% of total household utilization (Aberilla et al., 2020; Deng et al., 2020;Ruan et al., 2010). The used water from these activities is called *gray water*, and it is not heavily polluted. Contrasting is *black water*, with comes from toilet flushing. Black water is a relatively small fraction of the flow (parts of toilet flushing, only 3% of total household utilization) but contains most of the BOD, nitrogen, phosphorus, and bacteria of health concern (Gao et al., 2020).

Novel means to bring urban water demand into line with urban water supply must focus on all types of water flows, not just household flow. As the blue line in Fig. 2(a) shows, storm water can be collected to be part of the supply, and gray water and black water also can be treated and returned as a supply. Thus, "*wasted waters*" become new sources. Projects of "*wasted waters*" reuse have been applied, but some of them were not successful at last, such as application in Hamburg (German). Public Utilities Board in Singapore processed water reclamation and reuse in 1966 but failed because of costly and unreliable technology (Kog, 2020). Public acceptance of recycled water also inhibited "*wasted waters*" reuse project promotion, such as failure cases of Toilet to Tap campaign in California (USA) and Drinking Sewage campaign in Toowoomba (Australia) (Fielding et al., 2019). In South Africa, differences of management, maintenance, contradictory between national and provincial level also cause problems in all "*wasted waters*" reuse projects (Mendoza-Espinosa et al., 2019). Consequently, new paradigm for managing *wasted waters* should be provided.

Figure 2(b) shows a new paradigm for managing *wasted waters* so that they become tools for combatting urban water scarcity, not factors that exacerbate scarcity. The paradigm is called *5R generation*: *Recover* (*storm water*), *Reduce* (*toilet flushing water*), *Recycle* (*gray water*), *Resource* (*black water*), and *Reuse (advanced-treated water from wastewater)*. The *5R generation* integrates newer technologies, available for practice only in recent years, to gradually replace traditional wastewater treatment systems to enhance water utilization. The *5R* will be most applicable in common-use settings, such as community and shopping centers, hotels, and office buildings.

While a few *5R*-like projects are being implemented today, most of them are focused on reusing waste, not on augmenting urban water. For example, Malaysia has built different form of *5R* (Recycle, Reuse, Reduce, Refuse, Repair) for waste reuse. Our emphasis is on developing new water-supply options for urban areas.

2 Principles of *5R* generation

2.1 Recover

Recover in *5R generation* focuses on urban storm water and includes technologies for collection, treatment, and storage. Usually considered a problem, urban storm water has the potential to provide a non-potable water supply for toilet flushing, firefighting, vehicle washing, street cleaning, dust control, and water features (Lundy et al., 2018). Environmental Protection Agency of USA has developed storm water management recommendations and requirements as early as 1979 (Taguchi et al., 2020), and 2/3 of island land surface of Singapore has been applied for storm

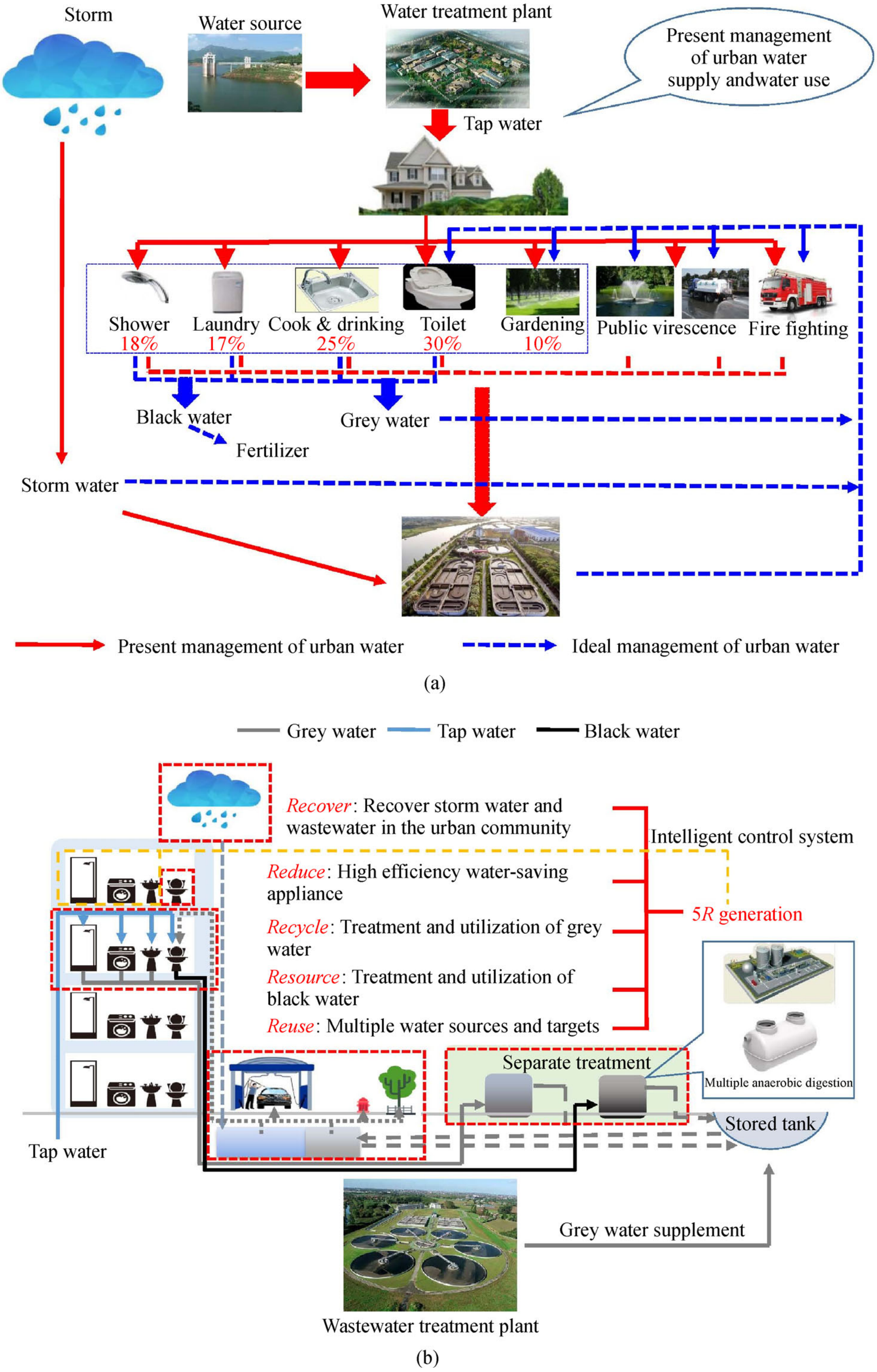


Fig. 2 (a) The present (red line) and ideal (blue line) management of urban water; (b) the framework of *5R* generation (black water is treated with multiple anaerobic digestion, such as UASB, in situ digestion).

water collection for water resource (Kog, 2020). Storm water often requires less treatment than municipal wastewaters, and its collection offers an added benefit of reducing pollution and erosion issues in receiving water bodies.

New technologies are making collection and treatment of storm water achievable. After storm water is collected from a drain, creek, roof, or pond, it can be treated to achieve quality requirements for different purposes (Taguchi et al., 2020). While many technologies for collecting and treating storm water have been available for some time, newer technologies are relevant for *Recover* in *5R generation*, depending on the local situation (Lorenzo and Kinzig, 2019). For example, a novel, highly cost-effective, and sustainable design for storm water collection for urban roads was built and operated in Nanjing (Jiangsu Province, China) (Cheng and Wang, 2018).

Storage is necessary for *Recover*, because precipitation events are sporadic, while demand is relatively uniform. Storage is a major challenge for *Recover*, because available open space in cities is limited. Traditionally, storm water is temporarily held behind dams or in tanks to balance supply and demand, but alternatives are being sought. Wetlands also are being applied for storm water storage (Tao et al., 2017). Dong'an Park in Sanya (Hainan Province, China) (Bai et al., 2018) and Jiading campuses of Tongji University (Shanghai, China; Fig. 3(a)) have built wetlands for storm water storage and its subsequent recovery. In the Caotang campus of Xi'an University of Architecture and Technology (Shaanxi Province, China, a demonstration for *Recover* in *5R generation* was built to collect storm water from roofs, and mobile treatment and storage of the storm water (Fig. 3(b)) can be used when rainfall is heavy.

2.2 Reduce

Reduce in *5R* generation mainly uses high efficiency, water-saving toilets to minimize the flushing volume, which contributes for approximate 30% of the black water flow. Reducing the water for flushing is a direct method to address scarcity in urban areas (Silva et al., 2017; Beler, 2019; Wu et al., 2019). Vacuum flushing already is widely applied for toilets in airplanes and high-speed trains, and it is beginning to be used in homes and hotels (Gao et al., 2019a). A vacuum toilet, such as the one shown in Fig. 4 (a1), uses only 0.5–2 L water (adjustable) per flush, compared to ~10 L/flush for a typical low-water-use toilet (Zhang et al., 2008; Gao et al., 2019b). EnviroSystems Company (Beijing, China), one of the contributors to *5R* generation, produces a water-saving toilet with urine and excrement separation (Fig. 4(a2)), and it only consumes 1–2 L water/flush for excrement and 0.1–0.5 L water/flush for urine due to its vacuum application. In addition, source-separation between urine and feces of toilet also protect the pipeline safety, because urine is dealt with gravity while only feces is treated with vacuum to load down the vacuum pressure (Hao et al., 2010). In 2010, the Dalian International Convention Center (Liaoning Province, China) installed more than 400 vacuum toilets and associated pipeline systems for it 132000-m^2 facility, and water savings have exceeded 70%. The program in Dalian International Convention Center (Liaoning Province, China) is the earliest model of *Reduce* in *5R generation*.

Moreover, different water-saving techniques, such as low-flow tap aerators in bathrooms, low-flow shower-heads, dual-flush cisterns, are widely applied for reducing water consumption. In Saudi Arabia, a residential building in Jeddah has applied above water-saving techniques and saving over 55% water consumption (Alsulaili et al., 2020). In USA, Proximity Hotel in North Carolina and Bardessono Hotel in California were both used water closets, dual-flush toilets, waterless urinals to reach 34% reduction in water consumption (Ahn and Pearce, 2013).

2.3 Recycle

Recycle in *5R* generation involves processing and recycling gray water in a household or community system. As Table 1 shows, gray water is generated from kitchen and bathroom sinks, showers and bathtubs, and laundry discharges, and it excludes toilet discharges (Li et al., 2009), which could be applied for toilet flushing and irrigation after reuse (Saumya et al., 2015; Oh et al., 2018). Based on civil wastewater calculation, 50%–70% of total domestic wastewater, which could be classified into gray water, only contains 30% of the organic matter and 9%–20% of the nutrients (Fountoulakis et al., 2016); thus, gray water is a plentiful source of relatively unpolluted urban

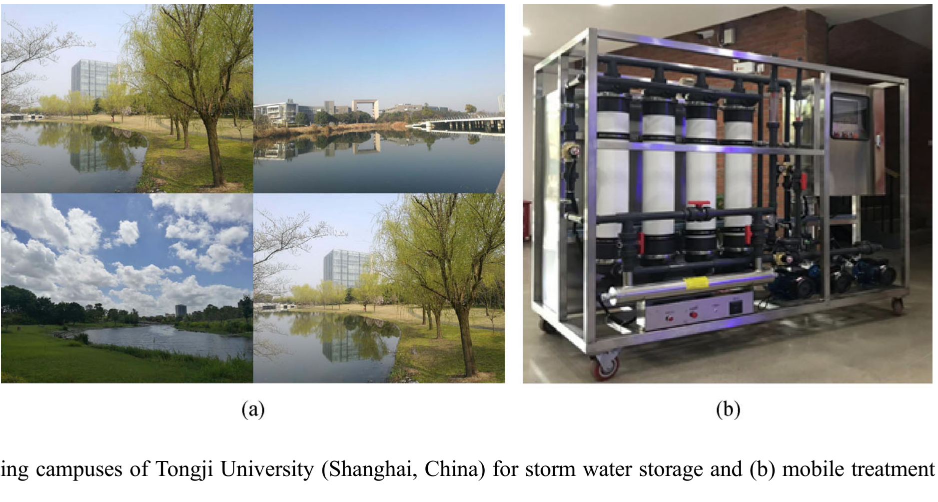

(a) (b)

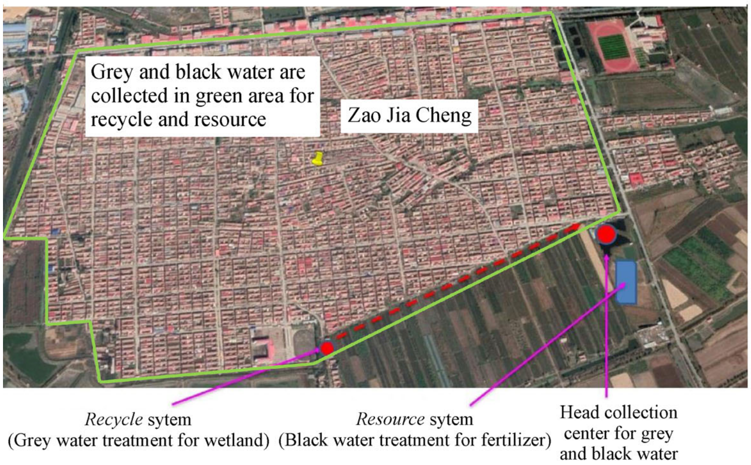
Fig. 3 (a) Jiading campuses of Tongji University (Shanghai, China) for storm water storage and (b) mobile treatment and storage for storm water.

(a)

Table Influent and effluent qualities for the membrane bioreactor treating wastewater and compared with China's water quality standard for urban miscellaneous water application

Indices	Influent	Effluent	Water quality (GB/T18920-2002)
pH	6.5−7.2	7.2−7.5	6.0−9.0
Turbid (NTU)	20−300	0.55−265	≤5
SS (mg/L)	65−300	0.55−3.10	—
COD_{Cr} (mg/L)	50−431	3−20	—
BOD_5 (mg/L)	40−80	1−2	≤10
NH_4^+-N (mg/L)	11−66	0.14−2.57	≤10
TN (mg/L)	17−81	1.20−35.06	—
TP (mg/L)	0.20−5.10	0.05−0.25	—

(b)



(c)

Fig. 4 (a) (1) A vacuum toilet which is being promoted for public restrooms in Nanning city (Guangxi Province, China), Haikou city (Hainan Province, China) and Beijing (China) (which has been widely applied in China high-speed railway train); (2) Toilet with urine (yellow water, which could be gray water after treatment, such as RO) and excrement (black water) separation from EnviroSystems Company; (b) Grey water treatment in Tongji University (Shanghai, China): (1) membrane bioreactor; (2) membrane module; (3) UF system; (4) Ion exchange system; (5) effluent; and (6) Membrane bioreactor performance; (c) a demonstration for *Recycle* and *Resource* in Zao Jia Cheng (Tianjin, China).

Table 1 Sources and characteristics of gray water and black water (De Gisi et al., 2016; Gao et al., 2019a; Prado et al., 2020; Welling et al., 2020)

Water	COD (mg/L)	TN (mg/L)	TP (mg/L)	pH
Grey water				
Kitchen and bathroom sinks, showers, bathtubs, laundry discharges, parts of toilet discharges (less polluted section)	100–700	1.7–34.3	0.11–22.8	6.3–8.1
Black water				
Parts of toilet discharges (polluted section), mainly containing feces with some urine and flushing water	990–1850	45–269	11.4–97	7.4–8.6

water (Revitt et al., 2011). According to lifestyle, living standard, population structure (age, gender), customs, water infrastructure, and the degree of water scarcity, gray water varies typically from 90 to 120 L/person/day, indicating a huge volume recyclable gray water as potential water source (Li et al., 2009).

In guideline and law section for gray water recycle, health and environmental impacts and risks are the first consideration for regulations and guidelines for reuse of gray water. But, WHO guidelines, which were released for gray water reuse for restricted and non-restricted agricultural irrigation in 2006, only outline microbiological requirements. Regulations established by local authorities may be more extensive. For example, the German Berliner Senate Office for Construction and Housing established a gray water reuse guideline, in which parameters like BOD, oxygen concentration, total coliform, fecal coliform, and *Pseudomonas aeruginosa* are required (Nolde, 2000).

In technological section for gray water recycle (Table 2), physical, chemical, and biological systems have been applied. For most of situations, a solid-liquid separation step as pre-treatment and followed by a disinfection step as post treatment is the traditional and effective process. In solid-liquid separation, pre-treatments (such as septic tank, filter bags, screen and filters) are applied to reduce the levels of particles, oil, and grease for avoiding clogging downstream treatment. Nowadays, coagulation, ion exchange, and photocatalytic oxidation are common physical-chemical processes for treating gray water (Pidou et al., 2008; Li et al., 2009). A disinfection step, like UV, NaClO addition, is used to meet the microbiological requirements (Li et al., 2009). Ward et al. (2015) reported that combinations of intermittently operated biologically active granular-activated carbon treatment with coagulation pretreatment and UF post-treatment resulted in sustained chemical-oxidant demand and turbidity reductions in excess of 90% and 99.5%, respectively. For example, Tongji University (Shanghai, China) has built and operated similar technologies for gray water treatment (Fig. 4(b)). In addition, separation of gray water from black water is an effective promotion for *Recycle*, and, ideally, it is integrated with the low-water-use toilets of *Reduce*, shown in Fig. 4(a1).

2.4 Resource

Resource in *5R* generation mainly involves capturing resources from black water in a household or community water system. Black water (Table 1) contains the highest discharge of organic compounds from a household, mainly from excrement. Black water also contains most of the N and P from urine (Jagtap and Boyer, 2018; Solanki and Boyer, 2019; Xue et al., 2020). As Fig. 2(a) shows, household wastewater normally is around 30% black water, making black water a non-trivial water source if it is not discharged immediately to the sewer. Separation of black water can be achieved with the toilets used in the *Resource* system (Fig. 4(a2)).

In previous studies (Larsen et al., 2016; Oh et al., 2018; Prado et al., 2020), black water was ignored in the water-recycle system, as it typically was discharged directly into a sewer for transport to a municipal wastewater treatment plant. Biochemical oxygen demand (BOD) and nutrients (phosphorus and nitrogen) usually are the most valuable

Table 2 Conventional/advanced technologies for gray water recycle (Boano et al., 2020)

Conventional/advanced technologies	Grey water origin	Removal efficiency of COD
Coagulation	Showers, sinks	64%
Electro-coagulation (EC)	Showers, sinks, kitchen	90%–95%
EC/O_3/UV	Showers, sinks	95%
Filtration	Shower, washing machine	20%
Rotating biological contactor	Laundry, bath, kitchen	21%–60%
Moving bed biofilm reactor	Laundry, bath	70%
MBR	Shower	86%
SBR	Shower	90%
UASB	Shower	51%

resources in black water. Li et al. (2015) reported that anaerobic membrane bioreactor or microbial electrochemical cells could capture most of the energy in the BOD, and turn black-water treatment into an energy-generating operation. They also pointed to emerging technologies, such a selective ion exchange and electrodialysis, for capturing and concentrate phosphorus and nitrogen for recycling to the agricultural sector. Recently, recovery of black water has become a heat topic, and anaerobic digestion is the most effective method for treatment and recovery of black water (Gao et al., 2019a). Zhang et al. (2020) and Koottatep et al. (2020) both figure out that thermophiles could effectively promote the treatment and re-resource of black water with anaerobic digestion. A demonstration for black water treatment and resource recovery (Fig. 4(c)) has been built and operated in "Zao Jia Cheng" village (Tianjin, China).

2.5 Reuse

Even when *Recover*, *Reduce*, *Recycle*, and *Resource* are well implemented in a community, some wastewater is going to a conventional wastewater-treatment plant. That water also can be reused for a range of purposes, as long as the effluent quality is sufficient for the purpose. Thus, *5R generation* includes *Reuse* to overcome water-quality deficiencies.

At municipal wastewater treatment plants, advanced treatment, which aims to remove suspended, colloidal, and dissolved constituents remaining after biological treatment, is applied to improve effluent quality. Bed filtration, surface filtration, micro- and ultra- filtration, reverse osmosis, electrodialysis, adsorption, air stripping, ion exchange, advanced oxidation, distillation, chemical precipitation, chemical oxidation, and disinfection are the typically advanced technologies used to improve effluent quality (De Gisi et al., 2016; Solanki and Boyer, 2019; Kog, 2020).

For maintaining water-quality during distribution, disinfection during pipeline transport usually is a necessity. Traditionally, chlorination is used, since it is simple, relatively inexpensive, and maintains a residual. However, chlorine over-dosing is a risk in large systems and can lead to formation of harmful disinfection by-products, tastes, and odors. To overcome the over-dosing problems, a *5R* demonstration project in Qingdao (China) applied automatic grid-disinfection (Fig. 5(a)) to maintain a small chlorine residual throughout the distribution system and without over-dosing at one location.

A second challenge with reuse is maintaining water pressure throughout the distribution system. This challenge is common to conventional water-distribution systems, but it is more significant for reuse, because many of its uses have sporadic, large demands: e.g., landscaping, garden irrigation, and car washes. In Singapore, water distribution with pipe transportation is one of most significant section for water reuse system (Kog, 2020). Water pipes system is also the main control of water system management, especially separation and distribution of clean, waste and reuse water (Marlow et al., 2013). The demonstration project of *5R* generation in Qingdao (China) uses an automated water-pressure-control system (Fig. 5(b)) to ensure that the distribution system meets all user needs. Additionally, wastewater treatment plants can set up reclaimed-water stations (analogous gas stations) to supply reclaimed water to vehicles that bring water to locations not served by the distribution network (Fig. 5(c)).

3 *5R* generation going on already in China

In previous engineering all over the world, Singapore has set up 17 reservoirs and collection pipes of 2/3 of island land surface for storm water catchment, and also processed NEWater project for high-grade reclaimed water from used water, especially with membrane application from 2003 (Kog, 2020). In South Africa, government published national and provincial level guideline for wastewater reuse, especially irrigation aim. Over 14% wastewater in South Africa from wastewater return flows of treatment plants is reclaimed as irrigation sources (Mendoza-Espinosa et al., 2019). But most of them just only contains parts of *5R* path. China has an outstanding opportunity to upgrade its urban water systems along the *5R* path. The door for this opportunity was opened wide in 2016 with the "National Key Research and Development Program of China". The program called for efficient development and utilization of water resource, and it provides funding for agricultural water-saving, seawater desalination, urban-water saving, and water-resource management.

The National Key Research and Development Program of China (2017YFC0403400) has funded *5R* development with 5.4 million US dollars. The *5R* generation will be installed and demonstrated for over 1.5 million m^2 of urban land surface area in Tianjin, Shanghai, Qingdao, and Xi'an, which represent among the driest and wettest cities in China. Tianjin, Shanghai, and Xi'an will progress gradually with different *R*s, and Qingdao has built a demonstration for *5R* generation. The long-term goal is to apply *5R* generation to upgrade water systems in at least 15% of residential community nationally.

Initial steps toward *5R* generation already are being implemented for different *R*s in China. For example, Tongji University (Shanghai, China) installed collection systems for storm, black, and gray waters (*Recover*, *Recycle*, and *Resource*), and they are given different levels of treatment for different reuse applications (Eichenseher, 2008). As shown in Fig. 4(b), the system includes a membrane bioreactor, ultrafiltration, reverse osmosis, disinfection, and ion exchange. The performance of the membrane bioreactor, shown in Fig. 4(b6), satisfies the Chinese standards for urban miscellaneous water applica-

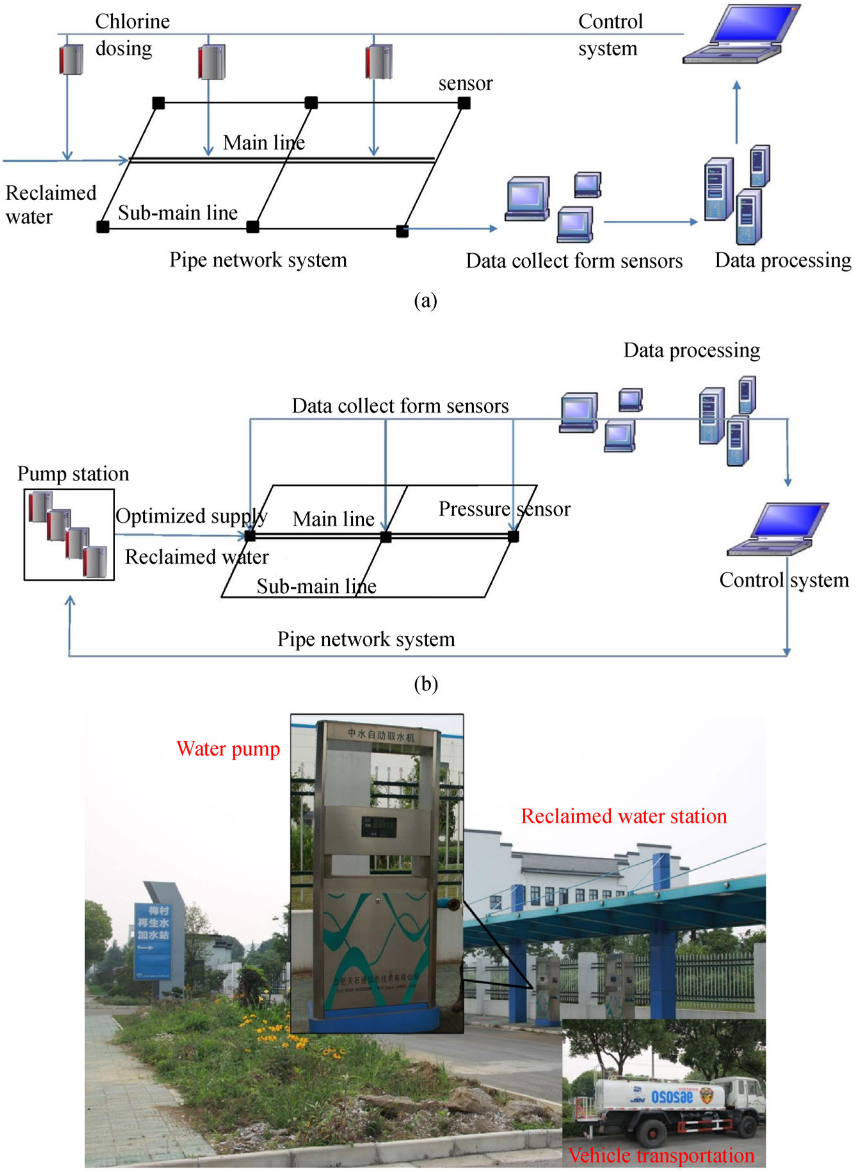


Fig. 5 (a) automatic grid-disinfection; (b) automatic water pressure balance control system; (c) Reclaimed water station in Meicun municipal wastewater treatment plant (Wuxi, Jiangsu Province, China).

tion. Hedian (a countryside area at Handan city in Hebei Province, China), which provides another initial step toward *5R* generation, applied vacuum toilets (Fig. 6(a)) and gray and black water separation in a 60000-m^2 community with over 150 houses (*Reduce*). As Fig. 6(a) shows, 50–80 m^3/d gray water and 3–5 m^3/d black water are separated and treated for household use through a central vacuum station. This system was built in 2013 and continues to operate stably. All of these initial steps are going to be upgraded to full *5R* generation. An example is black water for *Resource* in Hedian.

Recently, the city of Qingdao (Shandong province, China) set up and demonstrated the *5R* generation system illustrated in Fig. 6. This system is a semi-centralized supply for which water management is based on 5*R* generation (Fig. 6(b)). The community (noted as A and B in Fig. 6(b)), the Huatong hotel, and the Holiday Hotel separate gray water and black waters. After treatment, these waters are reused by communities, hotels, fire stations, the convention center, and the Shiyuan office building for flushing toilet (*Reduce*, *Recycle* and *Resource*). Water after treatment also is applied for the public uses, such as road cleaning and park irrigation. Moreover, rainwater is now collected and reclaimed with wetland system, and reclaimed water station is built up (*Recover* and *Reuse*). A smart station is also applied to

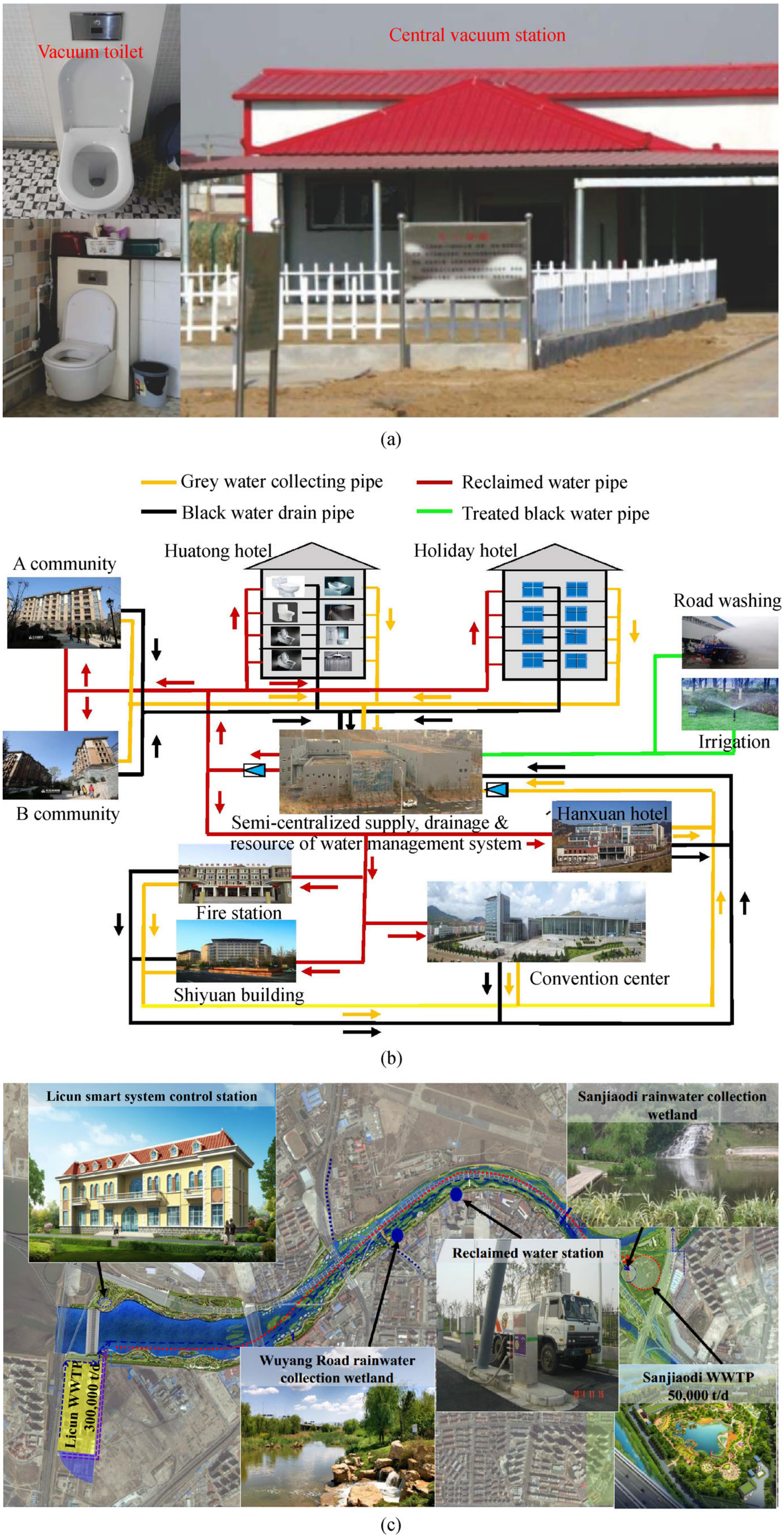


Fig. 6 (a) Vacuum toilet and the central vacuum station in the community center of Hedian (Shandong Province, China); Demonstration project of *5R* generation in Qingdao: (b) Community and hotel; (c) *Recovery* and *Reuse* system in Licun.

control the whole *5R* system in this area to guarantee a reliable quality and volume of water. This system is mainly based on the purpose of water saving and high effective water utilization for Expo 2014 of AIPH (Association Internationale des Producteurs de l'Horticulture) with "From the earth, for the Earth" theme, though cost and energy consumption of this system were similar as previous sustainable water projects.

With *5R* technology development, advanced *5R* projects have been demonstrated in Northern China, especially aiming to reduce water consumption and water multi-utilization in water-deficient area. A Licun smart station (Qingdao, China) (Fig. 6(c)) is also applied to control the whole *5R* system in this area to guarantee a reliable quality and volume of water. One of most significant purposes in this project is to apply reclaimed water for aesthetic environment use. Zao Jia Cheng (Tianjin, China) (Fig. 4(c)) has already set up a demonstration for *Recycle* and *Resource* to serve over 100000 people. Black water will be *resourced* for generate over 100000 tons of fertilizer, and gray water will be *recycled* for wetland irrigation. The governments of Licun (Qingdao, China) and Zao Jia Cheng (Tianjin, China) are considering other *R*s based on the on particular situation. The cost and energy consumption of this system had approximately 5%–10% decrease of previous sustainable water projects. Based on operational data of *5R* projects, the proportion of *Recovery* in *5R* system mainly depends on frequency of storm occurrence. The of *Reduce* parts could effectively save approximately 70% toilet water. The proportion of *Recycle* and *Resource* is, respectively, about 50%–70% of total domestic wastewater and 3% of total household utilization. *Reuse* proportion in *5R* system is according to the scale of water and wastewater transportation system.

4 Summary

Overall, any promising approach for solving urban water scarcity requires innovation and development in technology, organizational, and institutional dimensions, while newer technologies, available for practice only in recent years, to gradually replace traditional wastewater treatment systems to enhance water utilization. The novel *5R* approach for managing urban water resources includes *Recover* (*storm water*), *Reduce* (*toilet flushing water*), *Recycle* (*gray water*), *Resource* (*black water*), and *Reuse* (*advanced-treated wastewater*). It incorporates the latest ideas for harvesting storm water, gray water, and black water in its several forms. The *5R* will be most applicable in common-use settings, such as community and shopping centers, hotels, and office buildings. In China, demonstration projects of *5R* generation have been set up in Qingdao (China) and Dalian (China), achieving over 70% water saving. High-effective water utilization is kept to promoting with government and technologies, and more and more demonstrations of *5R* system are set up mainly and specially for water-saving. The *5R* offers promise for moving solutions for urban water scarcity from "hoped for in the future" to "realistic today".

Acknowledgements This study was funded by the National Key Research and Development Program of China (No. 2017YFC0403400). The authors declare that the publication of this paper presents no conflicts of interest. All present affiliations of all authors are indicated.

References

Aberilla J M, Gallego-Schmid A, Stamford L, Azapagic A (2020). Environmental assessment of domestic water supply options for remote communities. Water Research, 175: 115687

Ahn Y H, Pearce A R (2013). Green Luxury: a case study of two green hotels. Journal of Green Building, 8(1): 91–119

Alsulaili A D, Al-Matrouk M F, Al-Baghli R A, Al-Enezi A F (2020). Environmental and economic benefits of applying green building concepts in Kuwait. Environment, Development and Sustainability, 22(4): 3371–3387

Bai Z, Yu W Y, Zhang Y, Dong T Y, Lin G X (2018). From an ignored grey place to a resilient urban wetland—Dong'an Wetland Park in Sanya, Hainan Province. Landscape Architecture Frontiers, 6(3): 91–103 (in Chinese)

Beler B B (2019). Recycling/reusing grey water and yellow water (human urine): motivations, perspectives and reflections into the future. Desalination and Water Treatment, 172: 212–223

Boano F, Caruso A, Costamagna E, Ridolfi L, Fiore S, Demichelis F, Galvao A, Pisoeiro J, Rizzo A, Masi F (2020). A review of nature-based solutions for greywater treatment: Applications, hydraulic design, and environmental benefits. Science of the Total Environment, 711: 134731

Cheng Y N, Wang R J (2018). A novel stormwater management system for urban roads in China based on local conditions. Sustainable Cities and Society, 39: 163–171

Dai D, Sun M D, Xu X Q, Lei K (2019). Assessment of the water resource carrying capacity based on the ecological footprint: a case study in Zhangjiakou City, North China. Environmental Science and Pollution Research International, 26(11): 11000–11011

De Gisi S, Casella P, Notarnicola M, Farina R (2016). Grey water in buildings: a mini-review of guidelines, technologies and case studies. Civil Engineering and Environmental Systems, 33(1): 35–54

Deng H M, Wang C, Cai W J, Liu Y, Zhang L X (2020). Managing the water-energy-food nexus in China by adjusting critical final demands and supply chains: An input-output analysis. Science of the Total Environment, 720: 137635

Dunn G, Bos J J, Brown R R (2018). Mediating the science-policy interface: Insights from the urban water sector in Melbourne, Australia. Environmental Science & Policy, 82: 143–150

Eakin H, Lerner A M, Manuel-Navarrete D, Hernández Aguilar B, Martínez-Canedo A, Tellman B, Charli-Joseph L, Fernández Álvarez R, Bojórquez-Tapia L(2016). Adapting to risk and perpetuating poverty: Household's strategies for managing flood risk and water scarcity in Mexico City. Environmental Science & Policy, 66: 324–

333

Eichenseher T (2008). Just add (gray) water. Environmental Science & Technology, 42(7): 2210

Ercin A E, Hoekstra A Y (2014). Water footprint scenarios for 2050: A global analysis. Environment International, 64(3): 71–82

Fielding K S, Dolnicar S, Schultz T (2019). Public acceptance of recycled water. International Journal of Water Resources Development, 35(4): 551–586

Fountoulakis M S, Markakis N, Petousi I, Manios T (2016). Single house on-site grey water treatment using a submerged membrane bioreactor for toilet flushing. Science of the Total Environment, 551: 706–711

Gao M J, Guo B, Zhang L, Zhang Y D, Liu Y (2019a). Microbial community dynamics in anaerobic digesters treating conventional and vacuum toilet flushed blackwater. Water Research, 160: 249–258

Gao M J, Guo B, Zhang L, Zhang Y D, Yu N J W, Liu Y (2020). Biomethane recovery from source-diverted household blackwater: Impacts from feed sulfate. Process Safety and Environmental Protection, 136: 28–38

Gao M J, Zhang L, Florentino A P, Liu Y (2019b). Performance of anaerobic treatment of blackwater collected from different toilet flushing systems: Can we achieve both energy recovery and water conservation? Journal of Hazardous Materials, 365: 44–52

Hao X, Novotny V, Nelson V (2010). Water Infrastructure for Sustainable Communities: China and the World. Beijing: IWA, 1–7

Holmatov B, Lautze J, Manthrithilake H, Makin I (2017). Water security for productive economies: Applying an assessment framework in southern Africa. Physics and Chemistry of the Earth, 100: 258–269

Hong B, Lin Q Y, Yu S, Chen Y S, Chen Y M, Chiang P C (2018). Urbanization gradient of selected pharmaceuticals in surface water at a watershed scale. Science of the Total Environment, 634: 448–458

Jagtap N, Boyer T H (2018). Integrated, multi-process approach to total nutrient recovery from stored urine. Environmental Science. Water Research & Technology, 4(10): 1639–1650

Jensen O, Wu H J (2018). Urban water security indicators: Development and pilot. Environmental Science & Policy, 83: 33–45

Jiang X S, Qu Y X, Liu L Q, He Y, Li W C, Huang J, Yang H W, Yu G (2019). PPCPs in a drinking water treatment plant in the Yangtze River Delta of China: Occurrence, removal and risk assessment. Frontiers of Environmental Science and Engineering, 13(2): 27

Jiang Y (2009). China's water scarcity. Journal of Environmental Management, 90(11): 3185–3196

Judd S J (2017). Membrane technology costs and me. Water Research, 122: 1–9

Kim J, Kim J, Lee J, Yoo H (2018). Prediction of transverse settlement trough considering the combined effects of excavation and groundwater depression. Geomechanics and Engineering, 15(3): 851–859

Kog Y C (2020). Water reclamation and reuse in Singapore. Journal of Environmental Engineering, 146(4): 03120001

Koottatep T, Prapasriket P, Pussayanavin T, Polprasert C (2020). Performance of up-flow thermophilic septic tank treating blackwater. Environment, Development and Sustainability, 22(4): 3691–3700

Krzeminski P, Leverette L, Malamis S, Katsou E (2017). Membrane bioreactors- A review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects. Journal of Membrane Science, 527: 207–227

Kummu M, Ward P J, De Moel H, Varis O (2010). Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. Environmental Research Letters, 5(3): 034006

Larsen T A, Hoffmann S, Luthi C, Truffer B, Maurer M (2016). Emerging solutions to the water challenges of an urbanizing world. Science, 352(6288): 928–933

Li F, Wichmann K, Otterpohl R (2009). Review of the technological approaches for grey water treatment and reuses. Science of the Total Environment, 407(11): 3439–3449

Li W W, Yu H Q, Rittmann B E (2015). Chemistry: Reuse water pollutants. Nature, 528(7580): 29–31

Lorenzo T E, Kinzig A P (2019). Double exposures: future water security across urban Southeast Asia. Water, 12(1): 116

Lu Y L, Huang Y Q, Zeng S Y, Wang C (2020). Scenario-based assessment and multi-objective optimization of urban development plan with carrying capacity of water system. Frontiers of Environmental Science and Engineering, 14(2): 21

Lundy L, Revitt M, Ellis B (2018). An impact assessment for urban stormwater use. Environmental Science and Pollution Research International, 25(20): 19259–19270

Marlow D R, Moglia M, Cook S, Beale D J (2013). Towards sustainable urban water management: A critical reassessment. Water Research, 47(20): 7150–7161

Mcdonald R I, Weber K, Padowski J, Flörke M, Schneider C, Green P A, Gleeson T, Eckman S, Lehner B, Balk D, Boucher T, Grill G, Montgomery M (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. Global Environmental Change, 27: 96–105

Mekonnen M M, Hoekstra A Y (2016). Four billion people facing severe water scarcity. Science Advances, 2(2): e1500323

Mendoza-Espinosa L G, Burgess J E, Daessle L, Villada-Canela M (2019). Reclaimed water for the irrigation of vineyards: Mexico and South Africa as case studies. Sustainable Cities and Society, 51: 101769

Nolde E (2000). Greywater reuse systems for toilet flushing in multi-storey buildings: Over ten years experience in Berlin. Urban Water, 1 (4): 275–284

Oh K S, Leong J Y C, Poh P E, Chong M N, Lau E V (2018). A review of greywater recycling related issues: Challenges and future prospects, in Malaysia. Journal of Cleaner Production, 171: 17–29

Paiva A C D, Nascimento N, Rodriguez D A, Tomasella J, Carriello F, Rezende F S (2020). Urban expansion and its impact on water security: The case of the Paraiba do Sul River Basin, Sao Paulo, Brazil. Science of the Total Environment, 720: 137509

Pidou M, Avery L, Stephenson T, Jeffrey P, Parsons S A, Liu S, Memon F A, Jefferson B (2008). Chemical solutions for greywater recycling. Chemosphere, 71(1): 147–155

Prado L O, Souza H H S, Chiquito G M, Paulo P L, Boncz M A (2020). A comparison of different scenarios for on-site reuse of blackwater and kitchen waste using the life cycle assessment methodology. Environmental Impact Assessment Review, 82: 106362

Qu J H, Wang H C, Wang K J, Yu G, Ke B, Yu H Q, Ren H Q, Zheng X C (2019). Municipal wastewater treatment in China: Development history and future perspectives. Frontiers of Environmental Science and Engineering, 13(6): 88

Revitt D M, Eriksson E, Donner E (2011). The implications of household greywater treatment and reuse for municipal wastewater flows and micropollutant loads. Water Research, 45(4): 1549–1560

Rockström J, Falkenmark M, Allan T, Folke C, Gordon L, Jägerskog A, Kummu M, Lannerstad M, Meybeck M, Molden D (2015). The unfolding water drama in the Anthropocene: Towards a resilience - based perspective on water for global sustainability. Ecohydrology, 7 (5): 1249–1261

Ruan J L, Feng Y U, Chen H B, Liang Q, Wang S Y, He Q B (2010). Discussion on categorized collection and quality-based treatment of domestic sewage. China Water & Wastewater, 26(8): 25–29 (in Chinese)

Saumya S, Akansha S, Rinaldo J, Jayasri M A, Suthindhiran K (2015). Construction and evaluation of prototype subsurface flow wetland planted with *Heliconia angusta* for the treatment of synthetic greywater. Journal of Cleaner Production, 91: 235–240

Silva J K, Nunes L G C F, Soares A E P, Da Silva S R (2017). Assessment of water-saving equipment to support the urban management of water. Rbrh-Revista Brasileira De Recursos Hidricos, 22(0): e44

Solanki A, Boyer T H (2019). Physical-chemical interactions between pharmaceuticals and biochar in synthetic and real urine. Chemosphere, 218: 818–826

Song X Y, Luo W H, Hai F I, Price W E, Guo W S, Ngo H H, Nghiem L D (2018). Resource recovery from wastewater by anaerobic membrane bioreactors: Opportunities and challenges. Bioresource Technology, 270: 669–677

Taguchi V J, Weiss P T, Gulliver J S, Klein M R, Hozalski R M, Baker L A, Finlay J C, Keeler B L, Nieber J L (2020). It is not easy being green: recognizing unintended consequences of green stormwater infrastructure. Water (Basel), 12(2): 522

Tao W, Sauba K, Fattah K P, Smith J R (2017). Designing constructed wetlands for reclamation of pretreated wastewater and stormwater. Reviews in Environmental Science and Biotechnology, 16(1): 37–57

Vörösmarty C J, Green P, Salisbury J, Lammers R B (2000). Global water resources: Vulnerability from climate change and population growth. Science, 289(5477): 284–288

Ward L, Page M, Jurevis J, Nelson A, Rivera M, Hernandez M, Chappell M, Dusenbury J (2015). Assessment of biologically active GAC and complementary technologies for gray water treatment. Journal of Water Reuse and Desalination, 5(3): 239–249

Wei Y G, Wang Z C, Wang H W, Yao T, Li Y (2018). Promoting inclusive water governance and forecasting the structure of water consumption based on compositional data: A case study of Beijing. Science of the Total Environment, 634: 407–416

Welling C M, Sasidaran S, Kachoria P, Hennessy S, Lynch B J, Teleski S, Chaudhari H, Sellgren K L, Stoner B R, Grego S, Hawkins B T (2020). Field testing of a household-scale onsite blackwater treatment system in Coimbatore, India. Science of the Total Environment, 713: 136706

Wu D, Lam T P, Chan H Y, Lam K F, Zhou X D, Xu J Y, Sun K S, Ho P L (2019). A mixed-methods study on toilet hygiene practices among Chinese in Hong Kong. BMC Public Health, 19(1): 1654

Xue W C, Zaw M, An X C, Tabucanon A S (2020). Sea salt bittern-driven forward osmosis for nutrient recovery from black water: A dual waste-to-resource innovation via the osmotic membrane process. Frontiers of Environmental Science and Engineering, 14 (2): 32

Zhang J, Gao S B, Zhang J (2008). Application of vacuum toilet pan and vacuum sewer line for water saving and wastewater separation. Water and Wastewater Treatment Engineering, 34(2): 96–99 (in Chinese)

Zhang Q Y, Zhang L, Guo B, Liu Y (2020). Mesophiles outperform thermophiles in the anaerobic digestion of blackwater with kitchen residuals: Insights into process limitations. Waste Management, 105: 279–288