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Review

Urban drought challenge to 2030 sustainable development goals

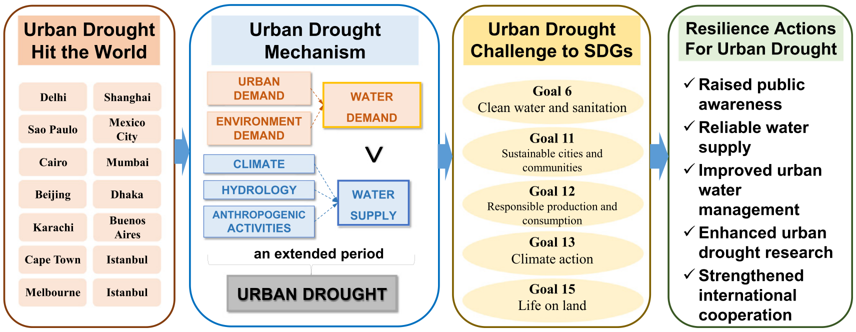
Xiang Zhang [a], Nengcheng Chen [a,*], Hao Sheng [b,*], Chris Ip [c], Long Yang [d], Yiqun Chen [e,f], Ziqin Sang [g], Tsegaye Tadesse [h], Tania Pei Yee Lim [i], Abbas Rajabifard [e,f], Cristina Bueti [c], Linglin Zeng [m], Brian Wardlow [h], Siqi Wang [a], Shiyi Tang [a], Zhang Xiong [b], Deren Li [a,j], Dev Niyogi [k,l]

[a] *State Key Laboratory of Information Engineering in Surveying, Mapping, and Remote Sensing (LIESMARS), Wuhan University, Wuhan 430079, China*
[b] *State Key Laboratory of Software Development Environment, School of Computer Science and Engineering, Beihang University, Beijing 100191, China*
[c] *International Telecommunication Union (ITU), 1211 Geneva 20, Switzerland*
[d] *School of Geography and Ocean Science, Nanjing University, Nanjing 210023, China*
[e] *Melbourne School of Engineering, The University of Melbourne, Parkville, VIC 3010, Australia*
[f] *Department of Infrastructure Engineering, Centre for SDIs and Land Administration (CSDILA), Melbourne School of Engineering, The University of Melbourne, Parkville, VIC 3010, Australia*
[g] *State Key Laboratory of Optical Communication Technologies and Networks, China Information Communication Technologies Group Corporation, Wuhan 430074, China*
[h] *National Drought Mitigation Center, University of Nebraska-Lincoln, Lincoln, NE 68583, USA*
[i] *United Nations Human Settlements Programme (UN-Habitat), Nairobi 00100, Kenya*
[j] *Collaborative Innovation Center of Geospatial Technology, Wuhan 430079, China*
[k] *Department of Agronomy-Crops, Soil, Environmental Science, Purdue University, West Lafayette, IN 47907, USA*
[l] *Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907, USA*
[m] *College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China.*

HIGHLIGHTS

- As a worldwide urban disaster, urban drought lacks thorough understanding.
- First perspective review on urban drought challenge to SDGs
- Urban drought is codetermined by multiple physical and anthropogenic factors.
- Five actions were proposed to build resilience to urban drought.

GRAPHICAL ABSTRACT



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ABSTRACT

In the first two decades of the 21st century, 79 global big cities have suffered extensively from drought disaster. Meanwhile, climate change has magnified urban drought in both frequency and severity, putting tremendous pressure on a city's water supply. Therefore, tackling the challenges of urban drought is an integral part of achieving the targets set in at least 5 different Sustainable Development Goals (SDGs). Yet, the current literatures on drought have not placed sufficient emphasis on urban drought challenge in achieving the United Nations' 2030 Agenda for Sustainable Development.

This review is intended to fill this knowledge gap by identifying the key concepts behind urban drought, including the definition, occurrence, characteristics, formation, and impacts. Then, four sub-categories of urban drought are proposed, including precipitation-induced, runoff-induced, pollution-induced, and demand-induced urban droughts. These sub-categories can support city stakeholders in taking drought mitigation actions and advancing

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* Corresponding author.
E-mail addresses: cnc@whu.edu.cn (N. Chen), shenghao@buaa.edu.cn (H. Sheng).

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SDGs
Sustainability
Urban

the following SDGs: SDG 6 “Clean water and sanitation”, SDG 11 “Sustainable cities and communities”, SDG 12 “Responsible production and consumption”, SDG 13 “Climate actions”, and SDG 15 “Life on land”.
To further support cities in taking concrete actions in reaching the listed SDGs, this perspective proposes five actions that city stakeholders can undertake in enhancing drought resilience and preparedness:1) Raising public awareness on water right and water saving; 2) Fostering flexible reliable, and integrated urban water supply; 3) Improving efficiency of urban water management; 4) Investing in sustainability science research for urban drought; and 5) Strengthening resilience efforts via international cooperation. In short, this review contains a wealth of insights on urban drought and highlights the intrinsic connections between drought resilience and the 2030 SDGs. It also proposes five action steps for policymakers and city stakeholders that would support them in taking the first step to combat and mitigate the impacts of urban droughts.

Contents

1. Introduction

While cities and urban areas cover only 3% of the Earth surface, approximately 54% of the global population currently live in cities. This aggregated distribution of population magnifies the consequences of a wide-array of urban disasters. Among them is urban drought, which has far-reaching consequences that are often overlooked by the scientific community (AghaKouchak et al., 2015; Editorial, 2018a). Urban drought directly impacts the ecosystem of a city, from agricultural yields, to industrial productivity, the health of city's inhabitants, and social stability. Such is the case in the recent urban droughts occurred in various cities including Los Angeles, Melbourne, Cape Town, Beijing, and Sao Paulo (Mao et al., 2015). Actually, many of the existing urban communities are still far from drought resilience, which is defined as the ability of urban water supply to thrive under drought and to continue to deliver its essential water service to humanity (Gleick, 2010; Gober et al., 2016; Meerow et al., 2016; Editorial, 2018b; Saja et al., 2019). However, the academia has not yet responded to this growing challenge. This calls for a renewed focus on urban drought.

It is estimated that there will be an additional 2 billion urban residents in 2030 and climate change will significantly alter the pattern and distribution of global water supply (Immerzeel et al., 2010; Trenberth, 2011; Taylor et al., 2013; Pan et al., 2017; Ahmadalipour et al., 2019). It is also predicted that more than 27% of the world major cities, with a total population of 233 million, will exhaust their current water resources by 2050 (Flörke et al., 2018). This trend will continue magnifying the severity of urban drought and put cities under tremendous water stress and drought risks (Ludwig et al., 2011; Gobiet et al., 2014; Schewe et al., 2014; Zhang et al., 2018b). Therefore, strengthening urban resilience to drought is recognized as one of the important tasks in achieving the 2030 Sustainable Development Goals (SDGs; Robert et al., 2005; Griggs et al., 2013).

Among the 17 SDGs proposed in the 2030 Agenda, at least 5 of them are directly associated with urban drought, including Goal 6 “Clean water and sanitation”, Goal 11 “Sustainable cities and communities”, Goal 12 “Responsible production and consumption”, Goal 13 “Climate action”, and Goal 15 “Life on land” (Nilsson et al., 2016). Each goal is connected to a set of targets and indicators. In order to achieve these targets, collective actions from the academia, public, policymakers, decision makers, and other relevant stakeholders are required. To that end, this paper aims to present a comprehensive overview on urban drought from the Anthropocene perspective (Van Loon et al., 2016) including its characteristics, impacts and formation mechanism. It then follows by the proposal of five concrete actions that city stakeholders can take in enhancing urban drought resilience and achieving different Sustainable Development Goals.

2. Urban drought as an increasingly significant worldwide phenomenon

2.1. Urban drought definition

There are four types of drought, including meteorological drought, hydrological drought, agricultural drought, and socio-economic drought. Each represents a temporary water shortage in precipitation, ground water, crop and urban life respectively (Wilhite and Glantz, 1985; Wilhite, 2000). In particular, socio-economic drought is associated with the supply and demand of economic good (e.g. water, forage, food grains, fish, and hydroelectric power) with elements of meteorological, hydrological, and agricultural drought that include precipitation

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shortages, high demand of evapotranspiration, soil water deficits, and reduced groundwater or reservoir levels. In this context, we propose that urban drought is a subtype of socio-economic drought, which represents a temporary water shortage condition in urban area and urban life either due to a sharp decrease in water supply or a sudden increase in water demand. Urban drought has direct impacts on a city's well-being, including public health issues, strained economic situations, increased water prices, and an overall decrease of the life quality within the city.

2.2. Urban drought versus water scarcity

It is important to distinguish between the term “urban drought” and “water scarcity”. Both terms are being used to describe the imbalance between water supply and demand. According to the Food and Agriculture Organization, water scarcity is defined as “a gap between available supply and expressed demand of freshwater in a specified domain” (Steduto et al., 2017). In most cases, the terms urban drought and water scarcity are used interchangeably in the academia. However, this study would like make several important distinctions between them. First, the term urban drought places specific focus on the imbalance of water supply-demand in urban area whereas water scarcity can be used to describe all manner of water shortages in all geographic locations. Second, urban drought is used to describe a temporary other than long-term water stress. Third, urban drought itself can be a main cause of water scarcity, since urban drought represents the change of balance, while water scarcity mainly describes the imbalance state. For the above reasons, this study has opted to use the term urban drought to illustrate the need for enhancing water supply resilience in cities (see Table 1).

2.3. Urban drought occurrence and characteristics

According to our statistics, since the year of 2000, at least 79 global big cities have already suffered from urban drought disaster at least once, as shown in Fig. 1. In other words, urban drought occurs not only in arid or semi-arid regions but also in semi-humid and even humid regions. According to the World Wildlife Fund, metropolitan areas including Sydney, Houston, Shanghai, Mexico City, Chennai, Mumbai, Seoul, Istanbul, Los Angeles, Lagos, Beijing, Lima, Rio Janeiro, and Cape Town are all vulnerable to urban drought (Engel et al., 2011; Carrão et al., 2016). Therefore, it is imperative to recognize that urban drought is a global challenge that affects both developing and developed countries.

Unlike other urban disasters (e.g., flood, earthquake, and fire), urban drought happens silently and often without visible warnings. “Too often in Africa and the rest of the world, actions to manage drought risks kick in only after a drought bites,” said scientists when Cape Town was facing ‘Day Zero’ crisis in 2018. Moreover, a substantial increase in concurrent droughts and heatwaves was found not only in South Africa and United States (Mazdiyasni and AghaKouchak, 2015; Sheridan and Lee, 2018), but also in the rest of the world (Mueller and Seneviratne, 2012). This concurrent of extremes had caused devastating consequences to urban communities and the entire ecosystem (Ciais et al., 2005).

Table 1
Differences between the term of urban drought and water scarcity.

Term	Urban drought	Water scarcity
Definition	A temporal excess of demand over available water supply in an urban area	A gap between available supply and expressed demand of freshwater in a specified domain (Steduto et al., 2017)
Period	Temporary water stress	Long-term water stress
Focus	Change	State
Causality	Cause	Consequence

A further investigation into the four recent urban droughts that occurred in Los Angeles, Sao Paolo, Melbourne, and Cape Town can provide more insights on the causes and impacts of urban drought, as shown in Table 2.

It was found the water supply systems of Sao Paolo and Cape Town were consisted mostly of passive water reservoirs. These reservoirs depend heavily on the availability of natural rainfall and streamflow. And in many regions of the world, rule curves are still being used for operating dams and reservoirs (Wan et al., 2019), and seasonal (or even sub-seasonal) forecasts are not considered at all. This type of water supply lacks the resilience when facing drought shock. Global satellites have also observed that water reservoirs in many cities have shrunk sharply when facing drought (Gao et al., 2012; Tong et al., 2016; Busker et al., 2019; Yuan et al., 2019; Van Den Hoek et al., 2019). Moreover, a recent study in the US has indicated that droughts are associated with the increment of salinity in rivers, which further reduces the availability of safe water (Jones and van Vliet, 2018). In cities like Phoenix and Tucson, it was also found that severe droughts of 1, 5, and 10 year duration would severely stress the existing water supply/demand budgets (Barbara et al., 2002).

Access to clean water has long been recognized as human rights by the United Nations (Gleick, 1998), which is, however, often threatened by drought emergency (Vörösmarty et al., 2010). Cities such as Los Angeles and Melbourne had developed adaptive measures and progressive actions to mitigate the impacts of urban drought, while Sao Paulo and Cape Town were criticized for lagging behind in adopting water resilience strategies (see Table 2). However, few cities are equipped to tackle the long-term effects of drought due to multiple reasons. Therefore, it is crucial to recognize that building adaptive water supply capacity and increasing preparedness for urban drought are central pieces for the long-term sustainability of cities and the achievement of the United Nations 2030 Sustainable Development Agenda (Kates et al., 2001).

Another notable feature of urban drought is its chain effect. Risks brought on by urban drought can act like an infectious disease which can be spread over to other cities. For example, Macao imports over 200 thousand m^3 of fresh water from Zhuhai every day. However, if the upper stream of Zhuhai's water reservoir, the Xijiang River, encounters a hydrological drought, then not only Zhuhai, but Macao would also suffer from the same urban drought. Under such circumstance, Macao would turn to Hong Kong for water import, where the water source is from Shenzhen. This chain effect illustrates two points. First, should an urban drought occur in either one of those four cities, all four of them will suffer from the consequences of the same urban drought. And second, whether in the case of a city or any urban agglomeration, when the water supply depends only on a single water source, then it cannot be considered to be drought resilience. A similar chain also exists between Pakistan and India through the Indus, Jhelum and Chenab rivers, and other water-connected cities worldwide (Miner et al., 2009; Zawahri, 2009).

The chain effect of drought would also extend to other urban disasters such as wildfire, spread of disease, air pollution, migration of the most affected population, suicide, and other forms of social disturbance (Hanigan et al., 2012; O'Loughlin et al., 2012; Couttenier and Soubeyran, 2013; Maystadt and Ecker, 2014; Hu et al., 2019). In a context-sensitive model that examines the level of vulnerability of different population groups, it reveals drought has significantly contributed to the sustained conflict between agriculturally dependent groups and politically marginalized groups in undeveloped countries (von Uexkull et al., 2016; Ahmadalipour and Moradkhani, 2018).

3. Physical and anthropogenic mechanism of urban drought

3.1. Urban drought formation

From a nominal perspective, urban drought is caused by a temporary imbalance between city water supply and demand along with water

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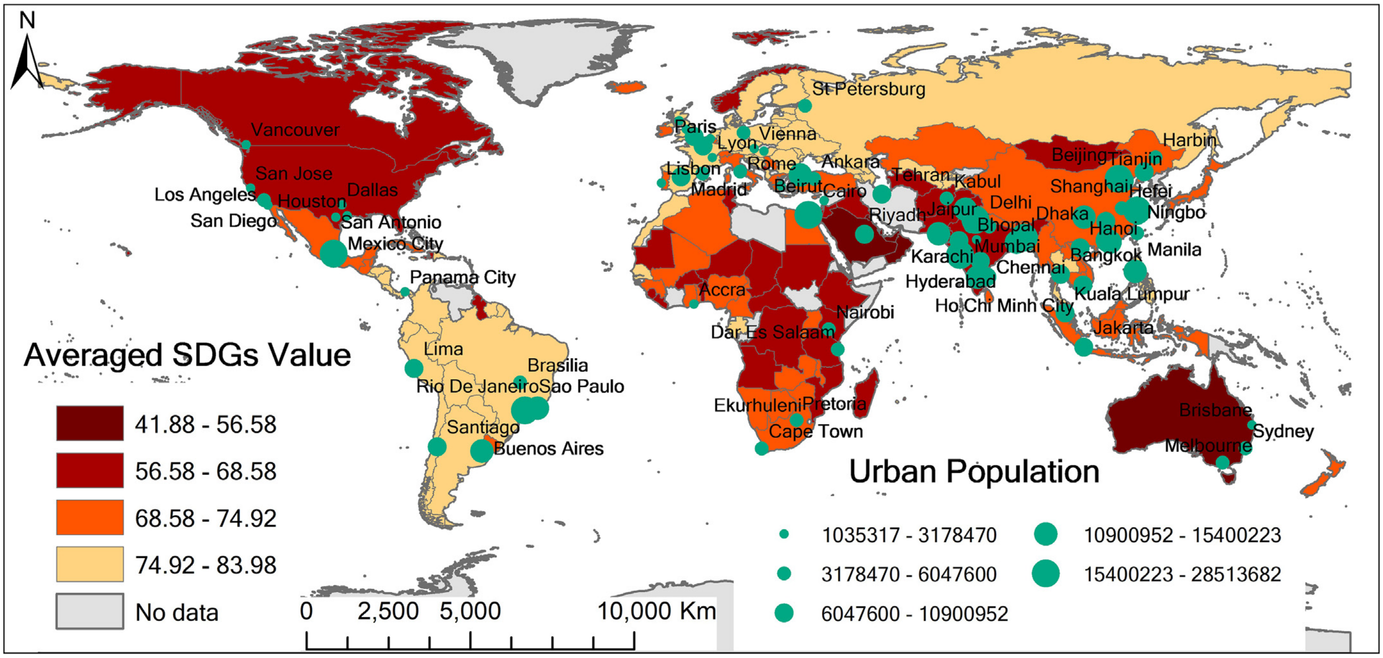

Fig. 1. Typical urban drought occurrences in global top 100 cities since 2000. Dark Cyan dots represent the urban population number in these cities in 2018 from the World Population Review. The SDG index value of every country was calculated by averaging SDG value of Goal 6, 11, 12, 13, and 15 of every countries in 2018 from the 2018 SDG Index and Dashboards Report, which tracks countries' progress towards achieving these SDGs (Sachs et al., 2016; Schmidt-Traub et al., 2017). High averaged SDG value represents the better achievement of these SDGs for each country. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mismanagement. However, if looking from a systemic perspective, the cause of urban drought is codetermined by multiple physical and anthropogenic factors that influence water supply and demands, including climate, hydrology, anthropogenic activities, urban demand, and environment demand, as shown in Fig. 2. In other words, urban drought is a typical disturbance of Coupled Human-Environment System (CHES; Turner et al., 2003a, 2003b).

On the one hand, the earth's climate system determines the total amount of potential water coming from precipitation, snowfall, and snow melt. On the other hand, climate also controls the evaporation and evapotranspiration processes, which deplete water from plant, soil, and surface. Meanwhile, a hydrologic system is responsible for the natural transfers of surface and underground water, thus controlling water availability (Pedro-Monzonís et al., 2015). Therefore, a mixture of climate and hydrologic systems controls the potential amount of water supply in a given urban area. While anthropogenic activities directly determine the actual water supply of a city, including water pipes and reservoirs construction, water desalination, water pollution, and etc. The most critical feature of a water distribution network is being able to redistribute water regardless of time, space and circumstances. A resilient network should be able to supply water even when under tremendous water stress.

Urban and environment water demands mainly determine the urban water requirement, including evaporation and evapotranspiration, residential, commercial and agricultural water uses. Urban water demand varies greatly depending on the cities, the time of day, and the behavior of the citizens (Diffenbaugh et al., 2015). When water demand is greater than water supply, which means when not all water requirements are fully satisfied, water shortage occurs. If the water shortage persists for so long that the adverse effects are beginning to appear in urban areas, then an urban drought occurs. In this process, a drought resilient infrastructure must be able to meet the most basic water needs of a city in order to extend the time before drought adversely affected our urban community.

It is also important to highlight the negative influence of human activities in the formation of urban drought. Activities such as dramatic changes of land use and land cover (LULC), overexploitation of underground water, and construction of massive glass curtain wall, have altered water cycle and water sustainability in irreversible ways (Turner et al., 2007; Howells et al., 2013; Zhang, 2013; Güneralp et al., 2015; Marston et al., 2015). The METROMEX project had already demonstrated that the sharp increase of impervious surface not only inhibited surface water infiltration and recharging rainfall groundwater, but also increased the reflectance energy when changing albedo, which in turn significantly influenced temperature and precipitation (Sarojini et al., 2016). Anthropogenic heat and urban aerosols also have significant impacts on urban hydroclimate (Diem and Brown, 2003; Cao et al., 2016). Therefore, it is crucial to take both physical and anthropogenic factors into consideration when understanding the mechanism of urban drought.

So far, this paper has shown that the formation of urban drought is codetermined by the balance between urban water supply (i.e., climate, hydrology, anthropogenic activities), water demand (urban water demand and environment water demand), and time. To better understand this physical and anthropogenic codetermining mechanism and the complex nature of urban drought, a new approach is required. This new approach would fall under the new urban science category (Acuto et al., 2018), in which the multidisciplinary knowledge from the natural, social, and engineering fields is the key.

3.2. Urban drought classification

In this review, we have adopted the above new approach. We propose to classify urban drought into four distinct categories: precipitation-induced urban drought, runoff-induced urban drought, pollution-induced urban drought, and demand-induced urban drought.

Precipitation-induced and runoff-induced droughts are the most common types of urban drought, which represents the temporal urban water supply deficiency due to lack of precipitation water and surface runoff water, respectively. Pollution-induced urban drought is quickly becoming a major concern as industrial activities are becoming more frequent and intense in most developing countries. Sewage water, industrial waste water and pesticide are affecting the water quality of water source and water distribution systems. As a result, the amount of usable water for a city is reduced (Masiá et al., 2015). For example,

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Table 2
Four representative and recent urban droughts across the global.

City and duration	Los Angeles (2012–2016)
Water supply	Complex and highly decentralized with over 400 utilities
Demonstration and impact	Record-high temperature, reduced water stored in the Sierra Nevada snowpack, below normal reservoir level, agricultural sector (especially rangeland grazing) in the first two years, then urban life
Action	Declare drought emergency, urban water use report; 20% voluntary conservation; mandate 25% water conservation; extend mandatory conservation regulations
Lesson	Coordinating water shortage contingency planning and implementation; Forster water system flexibility and integration; Improving water suppliers' fiscal resilience; Addressing water shortages in vulnerable communities and ecosystems; Balancing long-term water use efficiency and drought resilience
City and duration	Sao Paulo (2014–2015)
Water supply	Cantareira reservoir system
Demonstration and impact	Two dry raining seasons, lowest 3% capacity of reservoir, daily life and violent incidents
Action	Initial disorder actions, official water countdown
Lesson	Avoid pollution in reservoir and river, detection of urban drought in real time, long-term planning that integrates climate change and variability across all sectors of urban development
City and duration	Melbourne (2000—2010)
Water supply	Melbourne water consisted by 10 storage reservoirs
Demonstration and impact	Poor rainfall during the cool season and rainfall declines during the warm season, water storages had fallen to below 30%
Action	Reduced water demand per capita by almost 50%
Lesson	Prioritized conservation efforts, saving water with electronic billboards, purchase water rights for the environment, tax water authorities and use the money to promote sustainable water management and address adverse water-related environmental impacts
City and duration	Cape Town (2015–2018)
Water supply	Six reservoir dams around 900 million m^3
Demonstration and impact	Three consecutive years (2015–2017) of below average precipitation, below 20% of capacity of dams, local daily life and tourist industry
Action	Enforcing suburban restrictions of 50 l per person per day, 25 l a day when “day zero” begins
Lesson	Reducing water consumption, increasing water storage, improving the management of existing resources

it had been observed that the algae bloom in Taihu lake led to urban drought in the surrounding cities of China in 2007 (Duan et al., 2009). In addition, there is a risk of water supply terrorism in which the terrorists would target the urban water systems and pollute the water source in order to stop the supply of safe and clean water (Beering, 2002). Moreover, salt tide can also trigger urban drought when ocean water flows back into inland rivers, greatly reducing the availability of fresh water for coastal cities in Pearl River Delta and Yangtze River Delta, China for examples. However, there is yet to be a comprehensive program that covers all the necessary steps to ensure effective water quality monitoring (Behmel et al., 2016). Given that, a EU-FP7 funded project named SOLUTIONS has been established to explore the tools for the identification, prioritization and assessment of those water contaminants (Brack et al., 2015). We predict that pollution-induced urban drought will become more common in developing countries such as India, Brazil, South Africa, and China. This is part of the reason why the concept of “sustainable remediation” is proposed (Hou and Al-Tabbaa, 2014), which is a term adopted internationally and encompasses sustainable approaches to the investigation, assessment and management of potentially contaminated land and groundwater.

Demand-induced urban drought will be another nonnegligible issue for future cities. Urban water demand prediction is still facing the challenges of generating high accuracy forecasts and long-term estimations. However, existing simulation studies have shown that under the current anthropogenic and climate trends, the water demand is expected continue to increase until 2050 (Piao et al., 2010; Hejazi et al., 2014; Grouillet et al., 2015; Henriques et al., 2015; Flörke et al., 2018). Therefore, it is vital for cities to ensure that they have a sustained and growing water supply system that can meet the future water demand and minimize the risks of urban drought.

As previously discussed, though urban drought is described as a temporary water shortage situation, it can be evolved into a prolonged status of water shortage if the drought was accompanied by continuously low-rainfall or sequential droughts (i.e., long term water scarcity; Greve et al., 2018). Cities must take a proactive stance in defending against urban drought and cannot operate under the impression that urban drought is simply the result of an extreme weather event that is out of the cities' control.

4. Urban drought challenge to sustainable development goals

As demonstrated in Table 2, cities have implemented some measures to combat urban drought. Yet, it is clear that those measures are insufficient in mitigating the devastating consequences of urban drought. It is noted that urban drought would also more likely to disproportionately affect marginalized groups and population. Therefore, the majority of those who would be affected directly by urban drought live in developing countries. This contradicts directly to the motto of the UN 2030 Agenda for Sustainable Development Goal (SDGs), which is “leaving no one behind” (Griggs et al., 2013; Sachs, 2013; Stokstad, 2015).

After analyzing the SDG targets and corresponding indicators, this study found that urban drought is directly connected to at least five SDGs, twenty of their targets, and twenty-eight corresponding indicators at both national and city levels (ITU-T, 2016). The five SDGs include; Goal 6 “Clean water and sanitation”, Goal 11 “Sustainable cities and communities”, Goal 12 “Responsible production and consumption”, Goal 13 “Climate action”, and Goal 15 “Life on land”. The corresponding twenty targets and twenty-eight indicators are listed in Table 3. The specific content of these targets and indicators can be found in Griggs et al. (2013), Sachs (2013), Stokstad (2015), and United Nations (2018). In Table 3, we have further analyzed how urban drought aligns with each of the SDGs and their current progresses at the global scale (United Nations, 2018).

5. Building resilience to urban drought to achieve SDGs

To meet the challenges brought on by urban drought, we need rethink our resilience strategy and incorporate new priorities into a city's agenda. In this review, we propose the following five actions that city stakeholders can undertake to build resilience to urban drought and to achieve the associated SDGs. We acknowledge that the priority of each action is varied, but these actions as a whole are the fundamental steps towards making cities more resilient to urban drought.

5.1. Raising public awareness on water right and water saving

The urban drought in Cape Town reminds us that water does not automatically flow from our taps. This modern privilege is under threat from rapid urbanization and more frequent climate hazards. People are often unaware of drought until water restrictions are applied, while local water-use activities do have a global impact (Jaramillo and Destouni, 2015). Therefore, information transparency and access to water information play important roles in educating the public about the current water challenges. Awareness raising campaign is thus a valuable tool that enables informed decision making and encourages behavioral change (Grant et al., 2013; Attari, 2014). Therefore, the first action we propose is to provide educational tools to raise awareness

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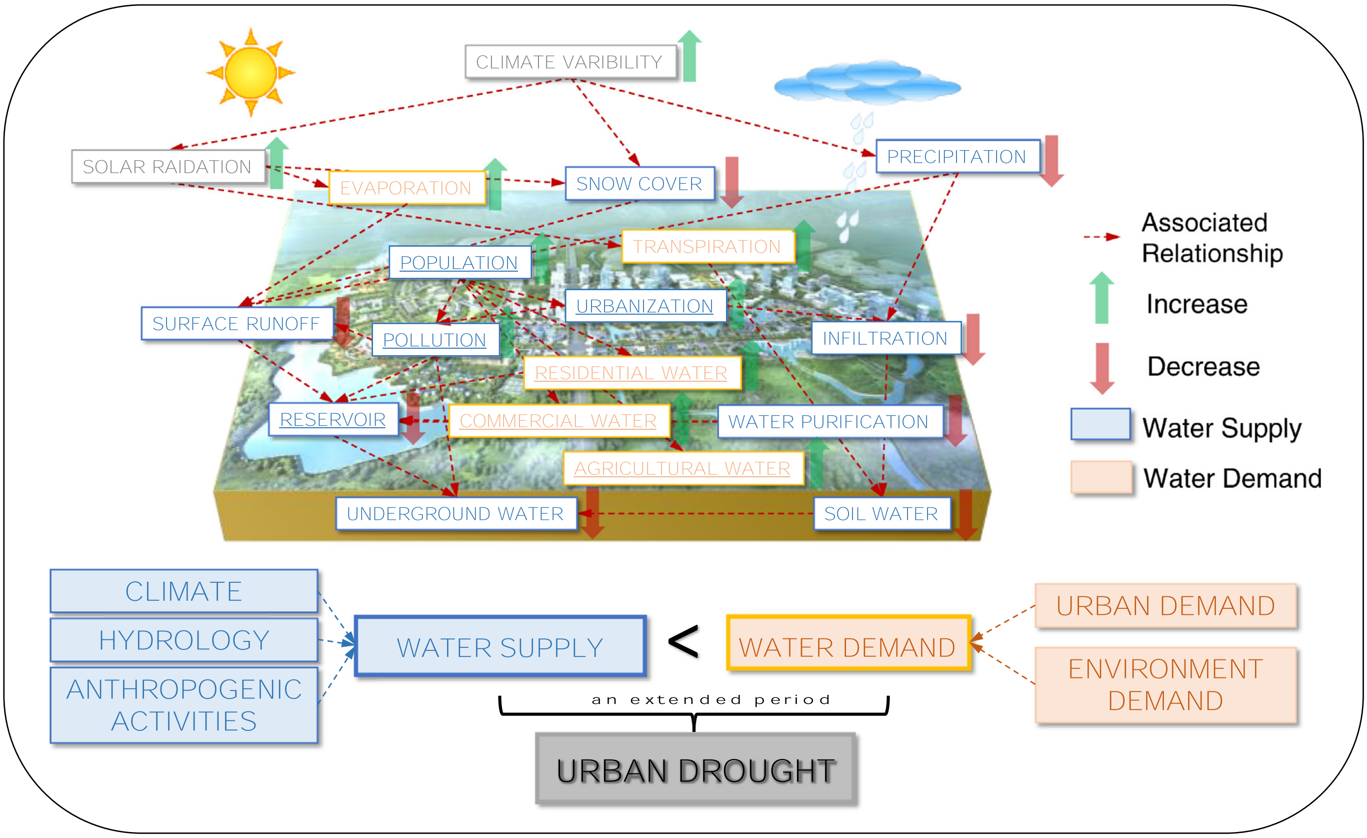

Fig. 2. Physical and anthropogenic mechanism of urban drought. The blue boxes represent water supplies for an urban area including climate, hydrology, and anthropogenic activities. The orange boxes represent urban and environment water demand. The red dashed arrows represent the associated relationship between two variables. The green and red arrows represent an increase and decrease of the corresponding variable during urban drought, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and understanding on urban drought, i.e. training drought-resilience residents.

First and foremost, water security is as vital as food security. A cohesive strategy that brings visibility to the challenges of urban drought and the international commitments that it associates with, including the SDGs and the Sendai framework for disaster risk reduction, is urgently needed (CDMPS, 2008; Aitsi-Selmi et al., 2015). It is important to disseminate the key facts on water usage at the international level. For example, the World Health Organization has observed that over 32% of water is wasted during use. Second, it is needed to promote behavioral changes among city dwellers and their water consumption habits. Encouraging citizens to alter their consumption patterns gives cities the best chance to avoid potential water crises. Evidences from global gravity satellites have already revealed that there is a clear “human fingerprint” on the global water cycle and freshwater is rapidly disappearing due to over consumption (Rodell et al., 2018). By educating people about water conservation policies, techniques and strategies, water usage will likely to be reduced, enhancing resiliency against urban drought crisis (Grant et al., 2013; Dilling et al., 2019). Besides the conventional educational approaches, it was also found that video games and other forms of media are effective means to raise awareness on key climate change issues including urban drought. This is particularly important when it comes to nurturing the next generation into caring about the consequences of urban drought (Wu and Lee, 2015). As extreme climate conditions continue to play a substantial role in shaping modern societies, urban drought disaster will also demand new responses and solutions from modern urban citizens (Carleton and Hsiang, 2016).

Raising awareness on water saving is equally important among different city sectors. For example, the agriculture sector alone accounts for around 70% of global water usage. It was also estimated that if water usage in agriculture was reduced by just 10%, the supply of drinkable water would be doubled. Farmers need to know that by improving irrigation techniques, such as trickle or drip irrigation, they could converse the use of water while improving crop yield. Studies have already shown that techniques such as recycling urban waste water for irrigation are particular suitable for water saving in urban agriculture (Palmer, 2018). Through awareness raising and knowledge dissemination activities, such water saving technique would be able to enhance the drought resilience of even the most water-stressed cities.

5.2. Fostering flexible, reliable, and integrated urban water supply

Climate change has rendered dams and reservoirs vulnerable to drought. City needs to diversity its water sources in order to avoid another “Day Zero” case like Cape Town. As demonstrated before, cities with only a single water source are susceptible to urban drought and its chain effect. Therefore, the water supply portfolio of a city should be diversified in order to enhance the reliability of water supply. Recent studies have highlighted the different alternative water sources including artificial rainfall, urban rainwater tanks, sea water desalination, storm-water utilization, sectional water transfer, wastewater reuse, and voluntary water trading (Elimelech and Phillip, 2011; Grafton et al., 2011, 2012; Grant et al., 2013). Among them, sea water desalination is particularly popular in coastal cities and is on the rise in places like Australia, Saudi Arabia, and Israel. However, desalination is still facing technical limitations and uncertainties. The cost associated with sea water desalinization is still relatively high. But certain utility companies are still willing to pay a higher price for seawater desalination because of its reliability in the drought scenario. Therefore, we believe there is

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Table 3
The interconnection between urban drought and SDGs at global scale. The specific content of these targets and indicators can be found in Griggs et al. (2013), Sachs (2013), Stokstad (2015), and United Nations (2018). Overall, it is found urban drought seriously will hinder the achievement the five SDGs with the poor performance of corresponding twenty eight indicators in the near future.

SDGs	Targets, indicators	Urban drought challenge to improve SDG indicators
Goal 6: clean water and sanitation	Target: 6.1, 6.3, 6.4, 6.5, 6.6, 6.A, 6.B Indicator: 6.1.1, 6.3.1, 6.3.2, 6.4.1, 6.4.2, 6.5.1, 6.5.2, 6.6.1, 6.a.1, 6.b.1	① In 2015, 29% of the global population lacked safely managed drinking water supplies (United Nations, 2018). This percentage will surge when facing urban drought disaster, especially in Northern Africa, Western Asia, and Central and Southern Asia regions, where water stress level is above 70% (United Nations, 2018). ② The 48% average of having implemented an integrated water resources management still needs to be improved especially when facing a drought shock. ③ Only 59% of national transboundary basins are covered by an operational arrangement (United Nations, 2018), which will lead to international conflicts when these water resources are being utilized to fight drought.
Goal 11: sustainable cities and communities	Target: 11.3, 11.5, 11.6, 11.B Indicator: 11.3.1, 11.5.1, 11.6.1, 11.b.1, 11.b.2	① The actual number of people living in slums has increased from 807 million to 883 million from 2000 to 2014 (United Nations, 2018). These people are particularly vulnerable to urban drought as slums often lack adequate water management facility and sustainable water supply. ② Though 75% of municipal solid waste is being collected, this waste is often not treated and disposed of in a sustainable and environmentally sound manner (United Nations, 2018). Such solid waste is a major pollutant to underground water around urban areas and water sources. ③ 90% of deaths attributed to disasters occurred in low- and middle-income countries from 1990 to 2013 (United Nations, 2018). Urban drought and heat wave contribute directly to hydropenia, risks of disease outbreak and heat wave.
Goal 12: responsible consumption and production	Target: 12.1, 12.2, 12.5, 12.8, 12.A Indicator: 12.1.1, 12.2.1, 12.2.2, 12.5.1, 12.8.1, 12.a.1	① By 2018, a total of 108 countries had national policies and initiatives relevant to sustainable consumption and production (United Nations, 2018) and more companies are now reporting on sustainability. However, there is still a lack of awareness on responsible water consumption in society as a whole. Mitigation strategies should also take a holistic and inclusive approach, bringing all relevant stakeholders for consultation. ② The water footprint per capita is a useful tool to measure water sustainability of a city and raise water awareness and develop drought emergency response.
Goal 13: climate action	Target: 13.1, 13.2, 13.3 Indicator: 13.1.1, 13.1.2, 13.1.3, 13.2.1, 13.3.1, 13.3.2	① Climate change was demonstrated by hydroclimate extreme events like urban drought. However, further examination of the interconnection between drought and climate change is still being studied. ② Except the United States of America, 175 Parties had ratified the Paris Agreement, and 10 had successfully completed their national adaptation plans for responding to climate change (United Nations, 2018). However, a specific adaptation plan for urban drought is still unknown to most countries.
Goal 15: life on land	Target: 15.3 Indicator: 15.3.1	① Although the Earth have become greener and the rate of forest loss has been cut by 25% since 2000–2005 (United Nations, 2018; Chen et al., 2019), the overall land degradation is still reducing useable water in our cities. ② Urban drought drives out local species, alters the structure of forest, induces wildfire, and causes other negative impacts on biodiversity.

a huge global business market opportunity in making alternative water sources affordable, accessible and reliable.

Meanwhile, cities with diversified water supplies should also shift their focuses on enhancing the efficiency and collaboration of all water suppliers, including national, state, and local water suppliers (Porse et al., 2018). A government-lead committee should be established to develop an urban's water supply system that could response to climate emergency such as drought (Mitchell et al., 2017). For cities that rely on transboundary rivers for water supply, it is recommended that those cities should look to international platforms to strengthen the reliability of their water supplies during emergency. In addition, every household should have a dual-water supply system with treated water for drinking and non-treated water for cleaning, watering, and flushing. This approach has been proven very successful in Paris for building resilience of water supply.

One of the most successful projects in diversifying water supply is the South-North Water Transfer Project in China (Zhang, 2009). The project aims to channel 44.8 billion m^3 of fresh water annually from the Yangtze River in southern China to the more arid and industrialized north cities (Beijing and Tianjin) through three canals. This project has significantly enhanced the water-supply resilience of Beijing since 2014, although the dispute of water rights between the south and north has never ended. In Australia, before the Millennium drought took place, water from dams was the sole source for agriculture, industry and residential consumption. The drought shifted the way Australia treated its water resources and subsequently six major seawater desalination plants were constructed to provide water to its major cities. Many state governments have also made efforts in building a "drought-proof" state with various solutions such as greywater recycling, offering government rebates for home-owners to install water tanks, and making tougher restrictions on industries. In India, the reoccurrence of drought has given rise to ambitious mega-projects such as the Interlinking of Rivers (ILR) project. This project will construct 15,000 km of new canals and around 3000 dams and storage to connect all the water resources in India. This project is expected to provide the much-needed extra water supply when India Monsoon fails to bring enough water to the cities.

Another approach to improve water supply is to reinvent the traditional urban fabric to allow natural water to be absorbed into the ground. Studies indicate that only 20% to 30% of rainwater infiltrates the ground in urban areas. This causes waterlogging and surface water pollution. To remedy that, cities such as Lingang, a new City in Shanghai, Berlin, Geneva, Beijing, and Singapore have implemented the "Sponge City" method to preserve rainwater and increase the availability of water for emergency use (Xia et al., 2017). This method consists of measurements such as building permeable pavements that are capable of storing runoff water and allowing water to drain to the soil, covering rooftops with plants and preserving wetlands in rural areas. Similar to how the root of a forest preserves natural water, these measurement help to store water during wet seasons and release it during dry seasons (Chan et al., 2018). However, the Sponge City method has also been criticized for its relatively high cost for implementation and low performance in reality. Therefore, further scientific, engineering, and economic researches for sponge city are required before it can be adopted by worldwide cities.

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5.3. Improving efficiency of urban water management

Urban water management, including the corresponding river basin management determines the overall efficiency of water resource usage (Pistocchi et al., 2017). There is still a lot of urban water managers who rely on outdated data and strategies. To improve efficiency of urban water management, we suggest that a Cyber-Physical System should be developed (CPS; Kim and Kumar, 2012) for the purpose of urban water management. Based on numerous web-ready sensors, World Wide Web, interoperable standards, and decentralized computers, the urban water CPS can obtain and analyze water data in real-time and control water infrastructures (i.e., every river, reservoir, pipe, factory, and household). The urban water CPS will be powered by cutting edge technologies including different Internet of Things-driven solutions (Atzori et al., 2010), Sensor Web (Zhang et al., 2018a), Spatial Cyberinfrastructure (Wright and Wang, 2011), Big Data Mining (Wu et al., 2014), and Cloud Computing (JoSEP et al., 2010). In particular, urban water big data will be valuable inputs for city managers and scientists to make informed decision and to develop a more sustainable approach to water management and consumption (Webster, 2018). One of the first urban water CPS paradigm developed by the international community was the Smart Water Management (SWM), which was proposed by the International Telecommunication Union (ITU) in 2014. The SWM project has been successfully tested in different cities worldwide (Gemma et al., 2014). We believe that this big data-driven approach will play a fundamental role in improving urban water resilience in the near future.

Conjunctive Water Management (CWM) is another key to improve water management efficiency, in which surface water and groundwater are used in combination to improve water availability and reliability. In particular, fresh water in wetlands should be paid special attentions (Creed et al., 2017). They are critical backup urban water supply sources in emergency situation. New approaches for freshwater sustainability are required to protect freshwater systems through periods of changing societal needs and scientifically informed adaptive management (Gleick, 2018), such as the Clean Water Rule introduced in the US in 2015, the EU-FP7 Project GLOBAQUA (Navarro-Ortega et al., 2015), and the EU-funded project MARS (Managing Auqatic ecosystems and water Resources under multiple Stress; Hering et al., 2015). In recent years, Poff et al. (2015) has proposed an innovative sustainable water management paradigm called Eco-Engineering Decision Scaling (EEDS). This approach can quantitatively explore the trade-offs in stake-holder-defined engineering and ecological performance metrics across a range of possible management actions under unknown future hydrological and climate states. Meanwhile, the Forecast Informed Reservoir Operations (FIRO) has also been proposed as a new management strategy for reservoir operation and water management (Anghileri et al., 2016; Turner et al., 2017). The FIRO approach uses data from watershed monitoring and modern weather and water forecasting to help water managers selectively retain or release water from reservoirs in a manner that reflects the current and forecasted weather conditions. Considering the multiple aspects of water management, an integrated evaluation of each strategy is warranted (Momblanch et al., 2015).

Improving water distribution is also important to enhance urban water management. In particular, reducing water losses in water transport within the distribution networks has a significant potential in saving a large volume of water (Abdulshaheed et al., 2017). The centuries-old plumbing system of London is leaking three billion liters of water every day. In France, an average of 25% of drinking water is lost to leakage in the distribution network (this reaches up to 40% in remote places). But locating and repairing leaks are challenging tasks, considering the size of water distribution networks. Meanwhile, it has been proven that by reducing the pressure of pipeline network at night, the loss of existing leakage can be greatly reduced. This also highlights the importance of building an urban water CPS to improve the intelligence of the whole water system.

5.4. Investing in sustainability science research for urban drought

Pioneering studies in climate change have given us the basic understandings of urban drought. For example, White (1935) discussed the effect of water on the lives of human beings. Baumann and Cleasby (1958) and Groopman (1968) investigated the effect of rainfall deficiency on the municipal water supplies in Iowa and New York City. The level of acceptance of water conservation measures in the cities of California was also evaluated during drought condition (Bruvold, 1979; Hoffman et al., 1979). However, there are still many unresolved scientific issues on urban drought which demand inputs and contributions from multidisciplinary studies.

First, a systematic, reliable, and high-precision numerical urban drought model should be established by deriving from the physical and anthropogenic mechanism discussed in the previous section. The most challenging part of developing this model is to quantify the diverse anthropogenic activities and the drought variables (Haddeland et al., 2014; Trenberth et al., 2015). A large number of datasets, including every aspects of an urban drought (i.e., big data in urban drought) will be needed to develop such a model. A recent study has shown that including water management in the numerical urban drought model resulted in more accurate discharge representation (He et al., 2017). After establishing the numerical urban drought model, the propagation of urban drought can be simulated and tested. The result will give valuable insights on how an urban drought develops in a particular area. This is one of the most promising tools for improving the sustainable management efficiency of urban drought.

Meanwhile, research on urban drought prediction is also needed, particularly at the seasonal and annual scales. Urban drought prediction is mainly consisted of climate prediction, hydrological prediction, water redistribution capability prediction, human activities prediction, and water demand prediction. Although it is still a great challenge to generate accurate seasonal climate and hydrological predictions (AghaKouchak et al., 2015), recent studies have demonstrated that post-processing of the hydrological ensembles substantially improves the accuracy of precipitation and hydrological forecasting (Madadgar et al., 2014; Roulin and Vannitsem, 2015; Khajehei and Moradkhani, 2017; Khajehei et al., 2018).

With regard to water redistribution capability prediction, it is closely related to anthropogenic factors, including management policy, infrastructure construction, and distribution allocation. This type of study will largely depend on the availability of geospatial analysis and artificial intelligence simulation. With regard to urban water demand prediction, recent studies have also demonstrated that the application of statistical, machine learning, and artificial intelligence methodologies are useful for highly accurate forecasting (Al-Zahrani and Abo-Monasar, 2015; Brentan et al., 2017; Zubaidi et al., 2018). To further reduce the uncertainty of prediction, Srinivasan et al. (2017) have proposed the socio-hydrological models, which can explicitly account for feedbacks between water and society at multiple scales and facilitate stakeholder participation. After obtaining the accurate prediction results and a reliable drought propagation model, scientists will have the foundation to build an urban drought prediction system. This prediction system would simulate a digital-twin city that projects the future possible drought scenarios. This digital-twin will give valuable insights to the disaster response department, allowing first responders to accurately pinpoint the epicenter of urban drought and the most affected areas (Gampe et al., 2016). However, it is important to keep in mind that the causes and impacts of every single drought are different. Using lessons from past drought to derive solutions and responses for future drought must be done with cautions (AghaKouchak et al., 2015).

Another promising research is the development of an urban drought index. Based on urban drought index, drought magnitude can be deduced for urban vulnerability and resilience analyses (Turner, 2010), which can link with SDGs. This index should be a user-friendly representation of temporary urban water shortage. The quality of this urban

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drought index will be closely related to the completeness and accuracy of the data input. Existing drought indices could be used as a reference, while urban vulnerability to drought and urban water consumption should also be taken into consideration (Buurman et al., 2017). Meanwhile, the United States Drought Monitor (USDM; Svoboda et al., 2002) can be a practical tool for urban drought cases.

5.5. Strengthening resilience efforts via international cooperation

To tackle the critical and global urban drought issue, we must also focus on fostering collaborative efforts among international city managers, academia, technical experts and all other relevant stakeholders. The far-reaching effects of urban drought and the complexity of its formation call for international communities to establish global platforms that would facilitate collective engagements on resolving this issue through an inclusive process.

The United Nations has already taken the lead in this regard. The UN specialized agency in Information and Communications Technology (ICT), International Telecommunication Union, has long recognized ICT as the key enabler for smart water management. To support cities in implementing ICT solution for urban water management, ITU-R Study Group 7 has already carried out standardization works that assist cities in developing weather satellites, radio-based meteorological aid systems, radar systems for tracking drought and other disasters, and various radio communication systems that can be used in emergency situations. ITU-T Study Group 5 on environment, climate change, and circular economy has also carried out standardization work that can assess the water footprint of cities and facilitate smart water management in urban areas. Meanwhile, ITU-T Study Group 2 has developed a standardized language for emergency rescue work which is vital when conducting urban disaster relief efforts. These are the global platforms that city stakeholders can proactively engage with to gain technical expertise on building urban drought resilience and to form strategic partnership with other similar actors. Other UN initiatives such as UN-Water and UN-Habitat have also been raising awareness on critical water issues and they are the ideal platforms for multi-lateral discussion on urban drought and associated SDGs.

In addition, it is also found that international food trade has led to enhanced savings in global water resources over time, which is named as virtual water trade network (Dalin et al., 2012). Therefore, other international organizations such as the World Trade Organization (WTO), Food and Agriculture Organization (FAO), and the Belt and Road Initiative (B&R) can also play important roles in solving urban drought issues.

6. Direction for future and pathways forward

The UN has warned that there will be 1.8 billion people experiencing absolute water scarcity in 2025, and two thirds of the world will be living under water-stressed conditions. Given that, urban drought is posing to become one of the most significant barriers in achieving the SDGs in the last 11 years. We have been witnessing the devastating consequences of urban drought throughout the world. Cities like Cape Town and Brasília had almost turned off the water taps for the first time in human history. Therefore, understanding, contextualizing, and meeting the challenge of urban drought to SDGs under UN 2030 Agenda are urgently needed.

In this systemic review, we firstly explored the mechanism of urban drought, highlighting its physical and anthropogenic driven factors. It suggested that urban drought was a sophisticated event codetermined by climate, hydrology, anthropogenic activities, urban and environment water demands. This transdisciplinary and cross-sectoral disaster has had far-reaching impacts on the global community. If we continue with business as usual, cities would only become more vulnerable to drought and likely to suffer the devastating consequences. Therefore, we call on further research on this topic particularly from the natural, engineering, and social science disciplines of the academia. In particular, it needs our deep understanding of the intricate relationships between human and the natural world.

To build resilience to urban drought and realize sustainable development, we have suggested five promising actions; 1) Raising public awareness on water right and water saving; 2) Fostering flexible, reliable, and integrated urban water supply; 3) Improving efficiency of urban water management; 4) Investing in sustainability science research for urban drought; and 5) Strengthening resilience efforts via international cooperation.

Though urban drought will continue to be one of the major threats to many cities in the world, we believe that its impacts can be minimized or even prevented as long as we are scientifically prepared. We encourage international policy makers, researchers, entrepreneurs, and non-government organization workers to work together on building urban resilience and meeting urban drought challenge to achieve SDGs under UN 2030 Agenda.

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Declaration of Competing Interest

The authors declare no competing financial interests.

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