Ensuring Domestic Water Security for Cities under Rapid Urbanisation and Climate Change Risks

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Abstract

There has been an exponential growth in the number of people living in urban areas since the middle of the 20^{th} century, and by the end of 2018 more than half of the world population lived in cities. This rapid urbanisation has created unprecedented challenges, among which the provision of domestic water has received increasing attention. Water is a basic need for humans and is the basis for socio-economic development. However, in many developing countries, governments have difficulties keeping pace with the fast rate of urbanisation due to limited financial resources and a lack of technical expertise. This ultimately results in a number of water-related problems, such the lack of provision of an adequate water supply and improper sanitation, degradation of ecosystems, and storm water management failures. Moreover, climate change is exacerbating these water related problems by influencing the hydrological cycle.

Today there are 400 million urban dwellers worldwide affected by water scarcity and 250 million people are without improved sanitation services, causing an estimated 3.4 million deaths annually through water-borne diseases. These figures will inevitably increase, as an 80% increase in water demand is projected by 2050. According to the American Meteorological Society, accessibility to a sufficient supply of clean water is one of the critical issues facing society in the 21^{st} century. Such issues are now receiving greater attention from politicians and policymakers, leading to increased research in this direction. This chapter provides insights to the problems leading to an unreliable and unsecure water supply in cities and identifies future water challenges that cities will face, as well as showing how water security is interlinked with various developmental domains. Furthermore, indicators used to measure domestic water security are explained and an index based on the amalgamation of those indicators is presented to facilitate a better understanding of urban water security.

Keywords: climate change, domestic water, urbanisation, water security

1. Introduction

Urbanisation refers to an increase in the population living in urban areas. Since the middle of the 20th century, the world has experienced a rapid increase in the number of people living in cities as a result of industrialisation. From about 30% in 1950, the percentage of people living in urban areas worldwide increased to more than 50% by the end of 2018 (Figure 1). This shift from rural to urban areas is unparalleled in history and is causing important socio-economic changes, notably outside Europe and North America where this trend is more pronounced (Satterthwaite, 2004). Globally, the number of cities with more than one million inhabitants recently reached 561, with 33 of them classified as mega cities with more than 10 million inhabitants (United Nations, 2018). Population data from the United Nations[1] show that during the period 1950-2018 the number of people living in cities increased by over three billion worldwide with this exponential growth in the number of urban dwellers projected to continue in the future (Figure 1). This increase in urban population is the result of a combination of factors, particularly migration from rural areas, the spatial expansion of cities and hence the conversion of rural into urban areas, and the high growth rate of the urban population. This trend in urbanisation is not uniform across countries, as it is affected by socio-economic development and political stability, with the most rapid rate of urbanisation found in developing countries (Satterthwaite, 2004; Srinivasan et al., 2012).

Around 50% of the world's urban population now lives in Asia (United Nations, 2018), with Africa and South America also having an increasing proportion of their population living in urban areas. The world's largest cities, which were once found only in Europe (e.g., London) and North America (e.g., New York City) are now located in Asia. For example, London and New York City were one of the largest urban centres in the early 1950s, with a population of approximately 8 and 7.8 million inhabitants[2,3], respectively. However, in the late 20th century, Tokyo (Japan) became the world's largest city with its population reaching 34.5 million inhabitants at the turn of the century. Moreover, this trend in urbanisation is expected to continue into the 21st century with the addition of more than 2.6 billion urban inhabitants worldwide by 2050 (United Nations, 2018). By that time urban dwellers will account for nearly two-thirds of the world population (~85% in developed countries and ~65% in

[1]https://www.un.org/en/development/desa/population/theme/urbanization/index.asp
[2]https://data.london.gov.uk/dataset/historic-census-population
[3]http://physics.bu.edu/~redner/projects/population/cities/newyork.html

developing countries) and it has been estimated that such an increase in population will require more than 3000 new big cities (Koop and Leeuwen, 2017).

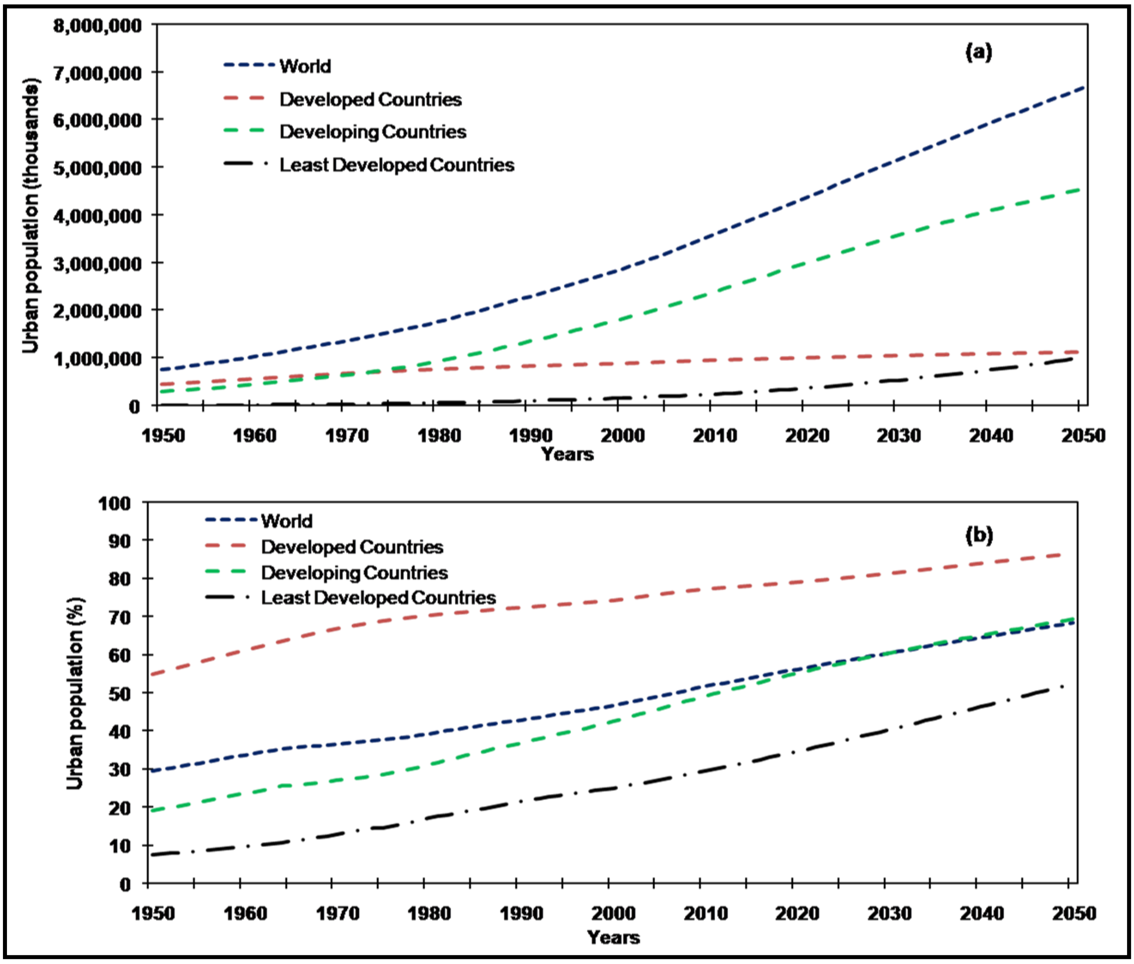

Figure 1: Growth in urban population from 1950 to 2050. The share of the urban population to the total population is shown in number (a) and in percentage (b) for the world and the developed, developing and least-developed countries.

2. The Challenges of Urbanisation

Rapid urbanisation has created unprecedented challenges with the provision of clean water gaining particular attention. Domestic water consumption, for instance, has increased more than four times in the last 60 years (Richter et al., 2013). However, in developing countries, governments, due to their limited resources and lack of technological knowledge, are unable to respond to this fast rate of urbanisation, which ultimately result in a variety of water-related problems, such as inadequate water supply, improper sanitation, degradation of ecosystems, and storm water management failures (Assefa et al., 2019).

New developments as a result of population growth are putting pressures on the urban environment, which contribute to the pollution of freshwater resources. According to CDP (2018), water quality issues affect 132 cities worldwide. This compares with 196 cities at risk of water stress (defined as per capita water availability of less than 1700 m^3 per year) or scarcity (defined as per capita water availability of less than 1000 m^3 per year). The majority of the approximately 400 million urban dwellers facing water scarcity live in Asia and Africa, (Bakker, 2012; Sperling and Serni, 2019), and 250 million are also without improved sanitation facilities, causing 3.4 million deaths annually due to water-borne diseases (Leeuwen, 2013). An improved sanitation facility is one that is connected to either a public sewer or a septic system. These figures are likely to become more severe in the future, as the demand for water is projected to rise by 80% by 2050, leading to a water crisis for about one billion urban dwellers worldwide (Amarasinghe and Smakhtin, 2014).

Although cities occupy approximately only two per cent of the surface area of the Earth, nearly 10% of the global water consumption takes place in cities (Hoekstra et al., 2012). Furthermore, one-fourth of urban areas are located in drylands where there are many cities with a population of more than one million inhabitants (Gunerlap et al., 2015; Koop and Leeuwen, 2017). In these water-deficient regions, more than 90% of the water is used for agriculture, which leaves very limited water for domestic usage (Richter et al., 2013). Hence, these cities suffer from periodic droughts and during those droughts the population relies on groundwater resources. This results in extensive pumping of groundwater, leading to a decline in the volume of groundwater in the aquifers and, in some cases, the depletion of the aquifer (Flörke et al., 2018). Figure 2 depicts the groundwater footprint of the world together with the location of the world's major cities. The groundwater footprint is the ratio of groundwater withdrawals to the estimated recharge in an area over a specific period of time. It is a unit-less ratio representing groundwater stress.

Moreover, most cities do not have their own water supply locally, and water is transported from surrounding regions. Surface water comprises an essential component of this water supply, accounting for approximately 80% of the total supplied water (McDonald et al., 2014). According to McDonald et al (2014), 504 billion litres of water are supplied daily to big cities by covering a total distance of 27,000 ± 3800 km, of which a significant proportion is lost because of leakage from water distribution networks. The situation becomes more critical during droughts, as the extremely dry soils affect the water supply distribution network by exerting pressure on pipes and joints (Gunerlap et al., 2015). Figure 3 depicts cities located in water stress regions. The baseline water stress is found to be very high for cities located in Southeast Asia, southern Europe and western North America. Furthermore, Gunerlap et al. (2015) predicted an expansion of urban areas into drylands by approximately 300,000 km^2 by 2030. In these environments cities are already short of water and this will cause even more stress on existing available water resources in the future.

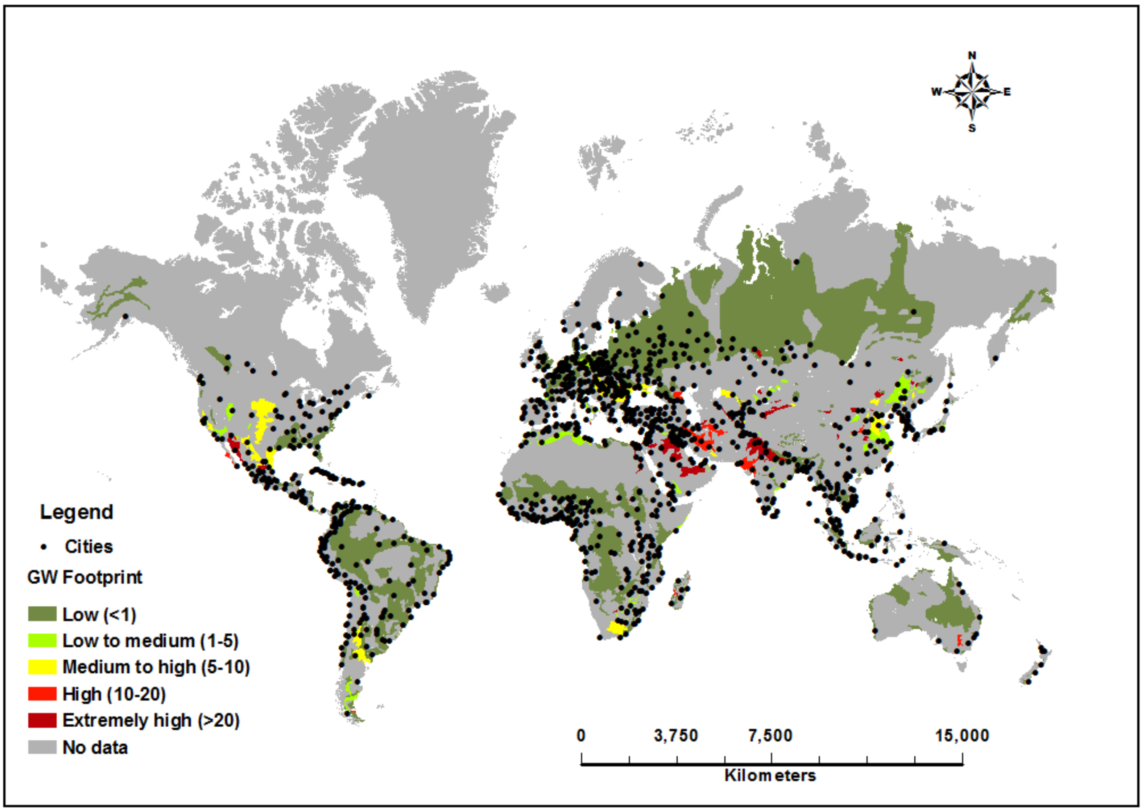

Figure 2: Global groundwater footprint (1958-2000). Map prepared using data obtained from the World Resources Institute[4] and showing cities with a population greater than 250,000 inhabitants falling under different categories of groundwater stress.

The estimated upstream storage of water for major cities across the world is shown in Figure 4. It assesses the potential of storing water upstream of a place with respect to the total water supply at that place. It is represented in the form of an index, which was obtained by dividing storage capacity to the mean of total blue water during the period 1950-2010. The figure clearly shows that cities in the eastern parts of Australia, North America and Asia, and the

[4]https://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data

western parts of South America and Africa are characterised by poor upstream water storage capacity. These cities are thus more exposed to the seasonal or long-term scarcity of water.

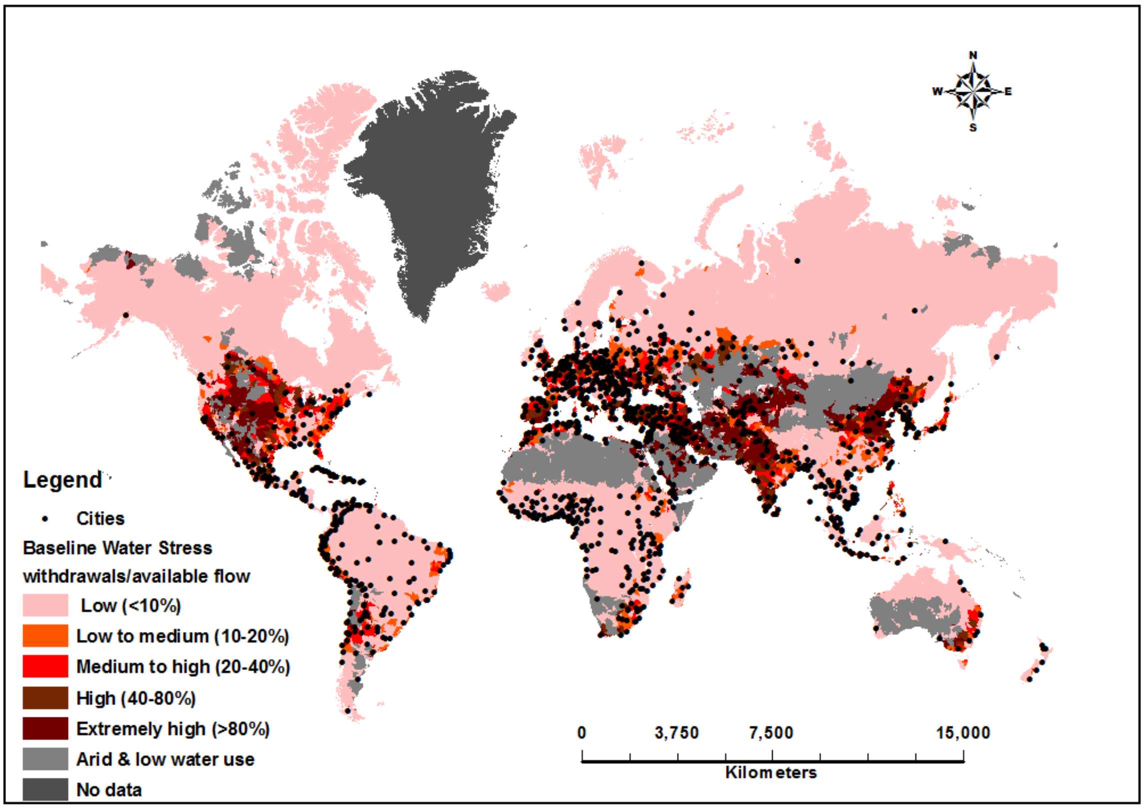

Figure 3: Global water stress index (1950-2010) showing the vulnerability of cities with a population greater than 250,000 inhabitants to freshwater availability. Source of data: https://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data

In addition to water management issues facing cities in relation to improved sanitation and water supply, there are other issues complicating the situation in cities of developing countries, notably an increasing population living in slums, the presence of various non-point pollution sources, a large percentage of the water supply lost through leakage and an aging distribution network. In a recent report, the United Nations (2015) revealed that around one billion people worldwide live in slums, of which the majority are found in developing countries where they account on average for about 30% of the population of a city. Based on current trends, this figure is projected to increase to two billion people by 2030 and three billion by the middle of the century (United Nations-Habitat, 2010). The lack of proper maintenance of the water infrastructure results in the loss of about 25% of the total water supply through leakage and evaporation. Additionally, only 10% of wastewater is treated prior to being released back into the environment because of the non-availability of low-cost treatment and lack of technological knowledge (Sperling and Serni, 2019).

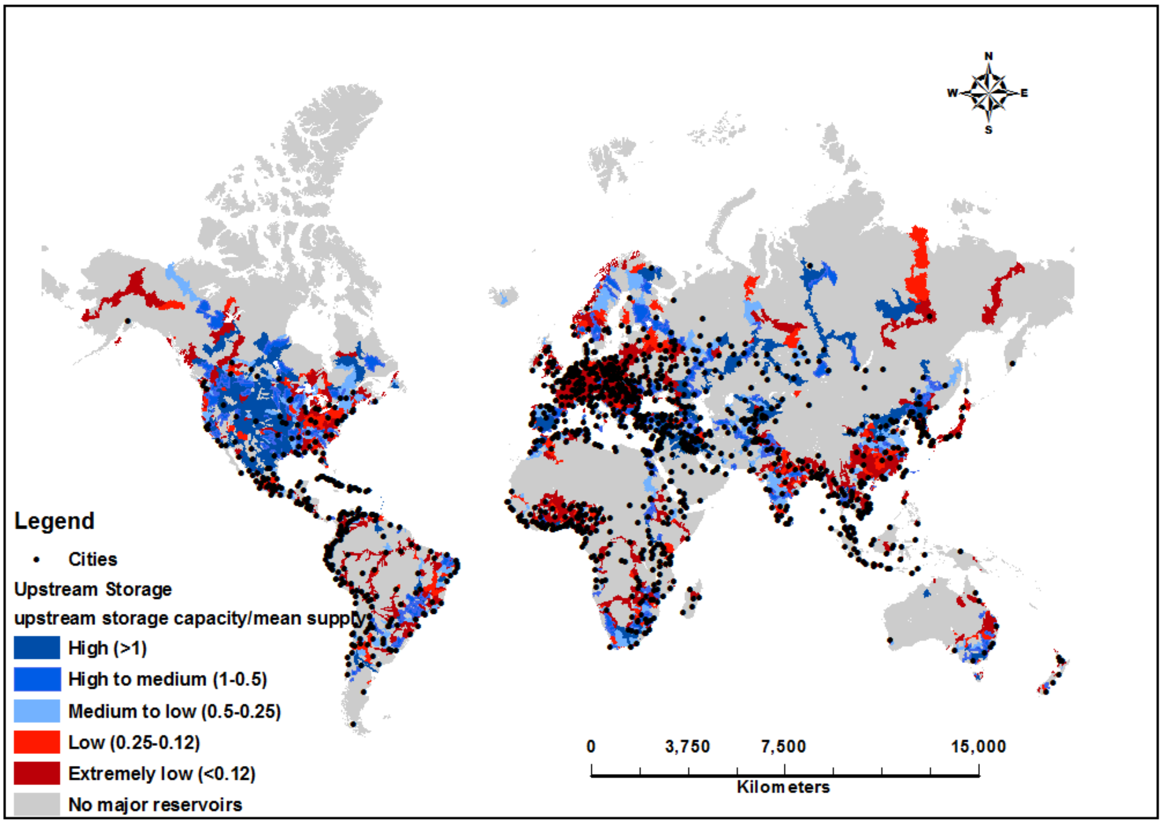

Figure 4: Global upstream water storage index (1950-2010). Source of data: https://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data

3. Climate Change and Water Scarcity

Fluctuations in temperature and precipitation impact on water resources in addition to long-term climate change (Afzal et al., 2015; 2016). The impact of climate variability, including extreme events, on water availability has long been an issue of concern and the focus of scientific research (e.g. Allen and Ingram (2002), Barnett et al. (2005)). Global mean surface temperature has recorded a rise of 0.74 ± 0.18°C throughout the 20th century (IPCC, 2013), while climate change has affected the amount, intensity and frequency of precipitation (Barnett et al., 2005; Singh et al., 2015). For instance, there has been an overall decrease in precipitation over land between 30°N and 10°S during the past few decades of the 20th century, with inevitable impacts on hydrologic parameters such as runoff and groundwater recharge. These climatic changes have resulted in a decrease in water availability, notably from glaciers, rivers, lakes, springs and reservoirs, leading to water shortages in many cities across the world (Gunerlap et al., 2015;Li et al., 2015). Globally, a correlation has been reported between climate change and the water crisis in cities (Wada et al., 2016; Flörke et al., 2018). CDP (2018) stated that 63% cities worldwide consider climate change as a threat to their water supply, with such perception of vulnerability higher in cities across Asia (84%) and Africa (80%) than in Europe (34%).

Climate change also increases the risk of extreme events (Easterling et al., 2000). The rise in global air temperature and extreme climatic events has led to an increase in the frequency and intensity of droughts, and has caused water crises in several cities across the world. This exemplified by the recent water crisis of California (2012-2017), Cape Town (2015-2018) and Melbourne (1996-2010), when these cities recorded their highest temperature and lowest annual rainfall on record. Figure 5 depicts the severity of droughts averaged over the period 1948-2008 and shows the average duration of periods of dryness (in month) for the world.

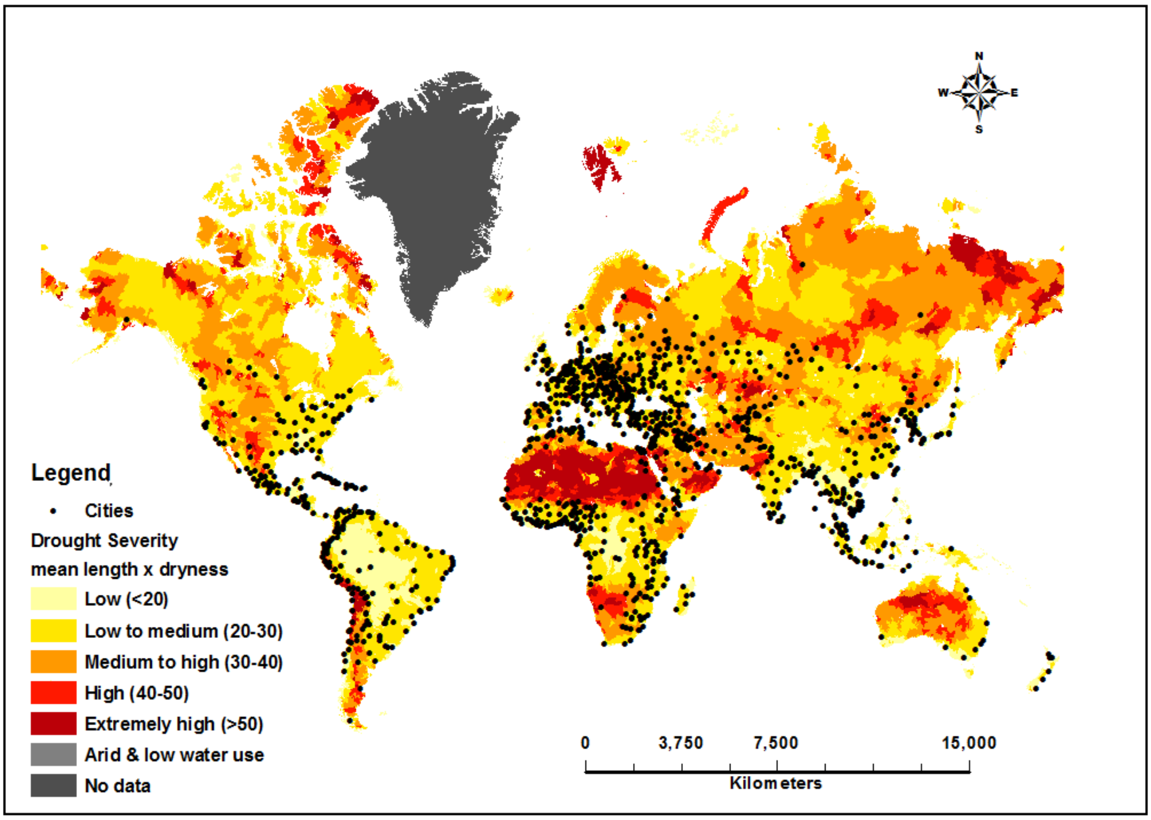

Figure 5: Drought severity map averaged over the period 1948-2008. Source of data: https://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data

According to the latest report published by the Intergovernmental Panel on Climate Change (IPCC), surface temperature is likely to increase by 1.5°C under a business as usual scenario by the end of the 21st century, with an associated increase in the number and frequency of extreme events (IPCC, 2013), with potential severe consequences for water resources. Guneralp et al. (2015) modelled the future expansion of urban areas and their exposure to climate change worldwide, and predicted a substantial expansion of urban areas into drought-prone areas, which is expected to increase from the 0.17 million km^2 in 2000 to 0.5 million km^2 by the end of 2030. The study, based on 482 large cities, reveals that the surface-water deficit will be in the range of 1,386 to 6,764 million m^3 for the 2050s under scenarios of climate change and shared socio-economic pathways. Approximately 27-40% of cities will face surface water shortages, escalating the urban groundwater footprint (Flörke et al., 2018) described above.

4. Urban Water Security

A reduction in the availability of water resources in cities has escalated conflicts in the distribution of water amongst users, including for the maintenance of ecosystems (Kurian, 2017). This also negatively affects the productivity of the urban systems, which may have serious implications on Gross World Product (GWP). Currently, cities provide approximately 80% of the total GWP (Dobbs et al., 2011). Therefore, the urban water crisis needs to be investigated with a broader perspective by considering the relationships among water resource sustainability, ecosystem health and economic development with water as the central determining factor (Chen and Shi, 2016). The first attempt in this direction was made during the Second World Water Forum and Ministerial Conference held at The Hague in 2000, where the term *water security* was introduced explicitly concerning the above discussed challenges.

Water security has been defined differently depending upon the subjectivity of the problems, but the notion of balancing the water requirements of humans and the environment remains the central objective of each definition (Bakker, 2012). According to Hoekstra et al. (2018), water security aims to achieve long-term sustainability by minimising risks associated with water, improving economic welfare and enhancing social equity. Thus, water security refers to a social state where everyone has access to safe and clean water, and the water could meet the demand for domestic users in addition to the demand for the agricultural and industrial sectors as well as to meet environmental flows required to maintain ecosystems (Assefa et al., 2019). Bakker (2012) has propagated water security as an emerging concept that adds value to the urban water management discourse. However, this notion of urban water security is somewhat distinct from the generalised concept of water security. This establishes parameters that are explicitly applicable for urban water security, and may not be useful for measuring water security at the global/country level. Romero-Lankao and Gnatz (2016) presented urban water security as a paradigm where developmental domains such as socio-demographic, economic, technological, and ecological and governance are mutually interrelated (Figure 6).

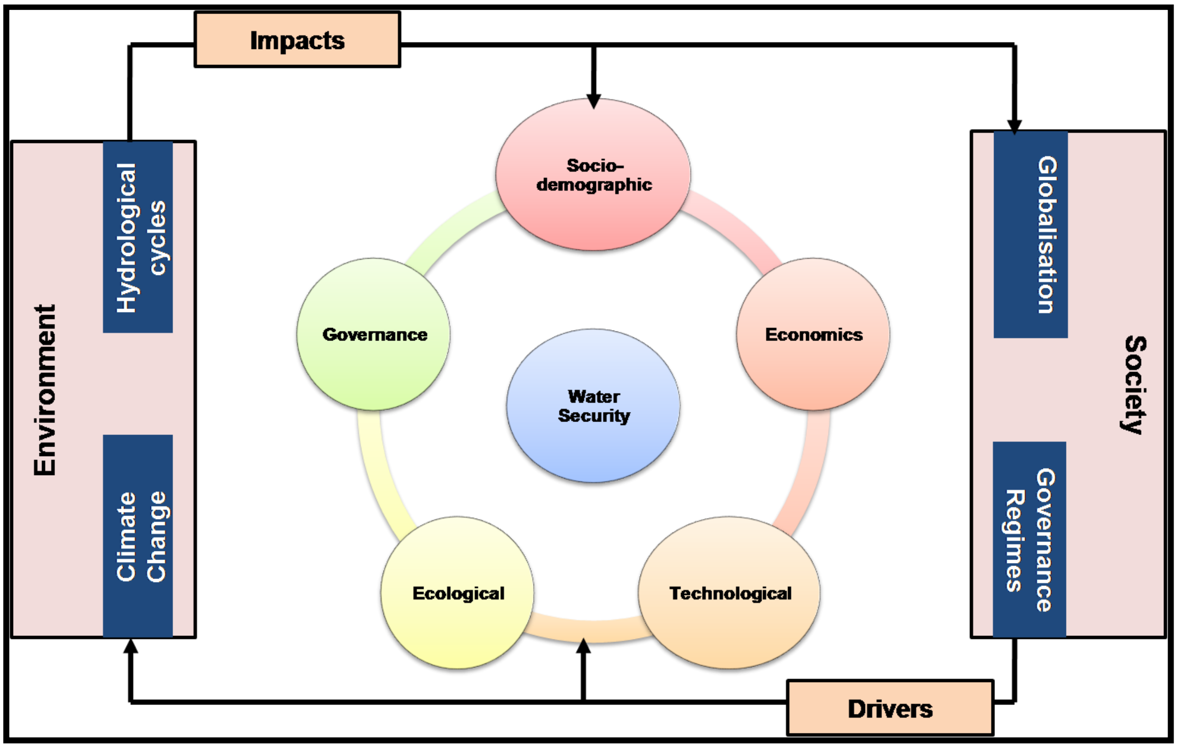

Figure 6: Influence of environmental and societal components on water security and its interaction with developmental domains (modified after Romero-Lankao and Gnatz (2016))

There are a very limited number of studies on urban water security, despite its immense significance in urban ecology, which might reflect the difficulty in measuring urban water security. The identification of relevant parameters/variables, and defining indicators that are truly representative of the different facets of urban water security is very challenging as these vary according to the scale of analysis, e.g., local, national or global (Jensen and Wu, 2018). Measuring urban water security at the global or national level will only provide the universal scenario of the problem from a countrywide standpoint, not from a local perspective. However, local indicators are helpful to show the variations that exist in water challenges between different localities within a single country or river basin, allowing for more effective problem identification, and to provide a stronger link between indicators and decision-makers, as responsibility for many aspects of water policy is widely devolved to the local level (Jensen and Wu, 2018). Furthermore, water security is highly dynamic (Srinivasan et al., 2017), suggesting the need for indicators that can reflect such changes at the local level. The assessment of urban water security is the foundation for establishing the strategy of water security and making management decisions.

5. Dimensions and Indicators

The dimensions and indicators used for measuring domestic urban water security are based on the criteria of the United Nations adopted for Sustainable Development Goals of clean water and sanitation (SDG6). The adopted dimensions include water supply, sanitation and hygiene. These dimensions of urban water security are expressed by sets, each including several indicators, which are defined by individual or group of variables. Assefa et al. (2019) describe these in detail.

i. Water supply dimension

This dimension of the domestic urban water security is mainly concerned with freshwater availability, its consumption, distribution and duration of supplied water. It provides an overall understanding of the availability of water resources, current demands and supply. The indicators/variables established for presenting this aspect of water security are elaborated on in the following paragraphs:

Per capita freshwater availability

Water availability is an important indicator and is expressed on per capita. It is calculated by dividing the size of the available water resource in a given year divided by the total population (Equation 1). If the availability of fresh water is less than 1700 and 1000 m^3/capita/year, the city is said to be in the state of water stress and water scarce, respectively.

$$\text{Per capita water availability} = \frac{\text{Total available freshwater resources } (m^3) \text{ in the year}}{\text{Total population of the year}} \qquad (1)$$

Per capita water consumption

Similar to water availability, water consumption is also a fundamental indicator, and is used in defining water supply dimension. This is represented by a variable known as per capita water consumption, which can be derived by dividing the total amount of water consumed to the total population (Equation 2). This variable is used to determine the current state of water consumption for routine household activities. It has been calculated that a consumption of 100 L/capita/day, all basic human needs are met, including hygiene (Howard and Bartram (2003).

$$\text{Per capita water consumption} = \frac{\text{Total amount of water consumed (L)}}{\text{Total population}} \quad (2)$$

Proportion of piped-water supply users in relation to total population

According to Hsu et al. (2014), improved water supply means that a facility or delivery point protects water from external contamination, particularly faecal contamination. This includes piped water to consumers. Therefore, the proportion of the population with piped water supply must be calculated to assess the status of improved water supply coverage of the city. This is measured as follows:

$$\text{Proportion of piped water supply} = \frac{\text{Number of piped water supply users}}{\text{Total population}} \times 100 \quad (3)$$

Water supply service duration per day

This factor is included in determining the duration of accessing improved water supply and continuity of the water supply service of the city, i.e., reliability of water supply. It is assumed that to say the city is well secured in terms of water supply; customers should have access to water for 24 hours per day.

Proportion of safe drinking water supply based on drinking water quality standards

Since the water quality directly impacts on human health, it is fundamental to assess the quality of the supplied water. According to WHO (2011), the recommended parameters of drinking water quality in community water supplies should include E. coli, residual chlorine, pH value and turbidity. Therefore, those parameters are assessed to check the status of the quality of water at each of the treatment plants in the study area. The WHO (2011) drinking water quality standards state that E. coli must be absent, residual chlorine must be greater than or equal to 0.2 mg/L, pH value must be between 6.5 and 8.5, and turbidity must be equal or less than 5 NTU.

Affordability of domestic water supply tariff

Affordability means that the water supply should consider low-income people so that all of the community can have access to a water supply. A tariff of about 0.40 US$/$m^3$can be taken as a benchmark, following the study of Banerjee and Morella (2011), who propose this as an affordable tariff in developing countries. However, this may not be appropriate for developed countries. In such a scenario, the benchmark such as the amount of income (as a proportion) spent on water services may be more appropriate.

Percentage of Non-Revenue Water (NRW)

Water loss in the water supply system is a major issue in many developing countries. High water loss leads to a shortage of water to the customers and increased costs for the operator. Thus, the water loss of the city should be assessed to determine the water security status of the city.NRW reflects the difference between the amount of water supplied through the water distribution system and that billed to customers. This percentage includes real or physical losses like water leakage and apparent losses such as illegal connections and meter inaccuracies.

ii. Sanitation Dimension

Access to sanitation was measured by considering the population that has access to an improved sanitation system. Hsu et al. (2014) defines improved sanitation as access to a connection to a sewer system, connection to a septic system, ventilated pit latrine, and pour-flush latrine. In general, if the system hygienically separates human excreta from contact and is not public, it is considered improved.

Proportion of customers connected to the sewer system

The proportion of sewer line system users is considered to evaluate improved sanitation access. Coverage of improved sanitation in terms of the sewer-line system is calculated based on the number of customers connected to the sewerage system to the total population of the area (Equation 4).

$$\text{Proportion of sewer line users} = \frac{\text{Number of sewer lines users}}{\text{Total population}} \times 100 \qquad (4)$$

Percentage of treated wastewater

About 80% of the freshwater supplied to the customers is assumed to be returned to the drainage network as wastewater. This wastewater should be treated prior to be released to protect human health and the environment. Thus, determining the amount of treated wastewater will lead us to see the water security status of the city. A city with 100% wastewater treatment capacity will be the most secured city from this perspective.

Proportion of wastewater effluent quality based on wastewater discharge quality standards

The quality of the treated wastewater should be within the recommended range to protect human health and the environment. Assessing the quality of effluent will be helpful in determining the water security status of the study area.

Affordability of domestic wastewater collection tariff

Collection of wastewater through a sewerage system should be affordable to all. This will help in improving the health status of people. Therefore, it is vital to assess the affordability of the wastewater disposal tariff of the study area. This can be assessed based on a questionnaire survey.

iii. Hygiene Dimension

Availability of water is fundamental to human health. Under the hygiene dimension, the two indicators, namely water availability and awareness are evaluated.

Water Availability for Hygiene (per Capita Water Consumption)

According to Howard and Bartram (2003), consumption of 100 L/capita/day covers all basic human needs, including hygiene. This metric is measured in the same way as that of per capita water consumption (Equation 2).

Percentage of population with diarrhoea

Having a proper toilet system and hand wash facilities with adequate water will improve the hygiene status of a community. Diarrhoea is an indicator of a non-hygienic situation. This is a common disease in developing countries. Thus, the percentage of people with diarrhoea is a good representative to reflect the water security of a place. This can be obtained through household surveys or from secondary data from health centres and hospitals.

Education Level

Awareness is a basic requirement of the hygienic condition. It is assumed that more educated persons will have good hygienic conditions compared to less educated persons. Therefore, the education level is used as a proxy for the hygiene conditions of people

6. Measuring Domestic Urban Water Security

An index representing the overall water security requires aggregation of the values of the different variables, indicators, and dimensions. The aggregation equations were adopted from Onsomkrit (2015), who carried out water security assessments at the city scale.

The first step in the calculation of the domestic water security index is to give a score for each of the variables (*v*) according to their values. After all the variables (*x*) are assigned with their respective scores, the next step is to calculate the indicators (*y*), dimensions (*z*), and the overall domestic urban water security index (*DUWSI*).

The value of an indicator (P_{zy}) is calculated with respect to scores given to variables as below:

$$P_{zy} = \sum_{y=1}^{n} \sum_{z=1}^{m} w_{zyx} \times V_{zyx} \quad (5)$$

P_{zy}: the value of indicator y for dimension z; n: number of indicators in dimension z; m: number of variables in indicator y; w_{zyx}: weight given to variable x of indicator y of dimension j; V_{zyx}: score of variable x of indicator y of dimension z. The total of weights given to the variables equals 1.

The value of a dimension (Z_z) is calculated with respect to values of indicators:

$$Z_z = \sum_{y=1}^{n} w_{zy} \times P_{zy} \quad (6)$$

where $Z_z$is the value of dimension z, w_{zx} is weight given to indicator y of dimension z. The total of weights given to indicators equals 1.

DUWSI is calculated with respect to values of dimensions:

$$DUWSI = \sum_{z=1}^{n} w_z \times Z_z \qquad (7)$$

where *DUWSI* is domestic urban water security index, *n* is the number of dimensions, w_z is the weight given to dimension *z*, with the total weight of all dimensions adding to one.

If the measured value of *DUWSI* is 3.5 or above (on the scale of 0-5) is considered good, the city has a fairly satisfactory system and environment for facilitating water security. However, if it is less than 2.5, it raises concerns on every dimension of water security and asks for developing service-specific action plans on the water to begin streamlining adaptive responses (Assefa et al., 2019).

7. Conclusion

The provision of a secure supply of water to urban areas is one of the most important challenges of the 21st century. This chapter provided insights to the problems leading to an unreliable and unsecure domestic water supply in cities and identified future water challenges that cities will face. Several cities worldwide are facing the risk of water insecurity due to rapid urbanisation and climate change impacts. It is projected that the number of people living in cities will increase by approximately 2.6 billion by 2050 and the demand for water will increase globally by 55% from its current level due to the increased consumption of water in manufacturing, energy and domestic uses. At the same time, 40% less supply in global water is predicted due to climate change and the failure of existing water resources. This will cause a risk to water supply systems of cities and alter urban ecology, jeopardising urban resilience systems. Hence, it is essential to define and quantify urban water security so that necessary measures can be taken in advance to better mitigate the forthcoming risks. Thus this chapter discussed different aspects of urban water security and showed how water security is interlinked with various developmental domains, and then explained the dimensions and indicators used in the development of a domestic water security index. This chapter elaborated on the notion of domestic urban water security and provided a holistic but simplified description to facilitate its understanding.

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