

Supplementary information

Addressing water security: an overview

S1 Water security challenges around the world

Data from the Water Resources Institute shows that water stress varies immensely around the globe (WRI - World Resources Institute, 2019), as seen in the map below (Figure S1). The Middle East and North Africa, being geographically located in hot, desert like climate, are the most water-stressed areas in the world, making water availability a big challenge. Added to that, the increasing demand, due to population growth and urbanization in these areas with limited resources, increases the challenge of securing water for people and economic activities. The Middle East also faces increased demand due to influx from displaced people and instability due to political conflicts, adding other dimensions to their water management challenges (Aboelnga et al., 2020; Arcadis, 2016).

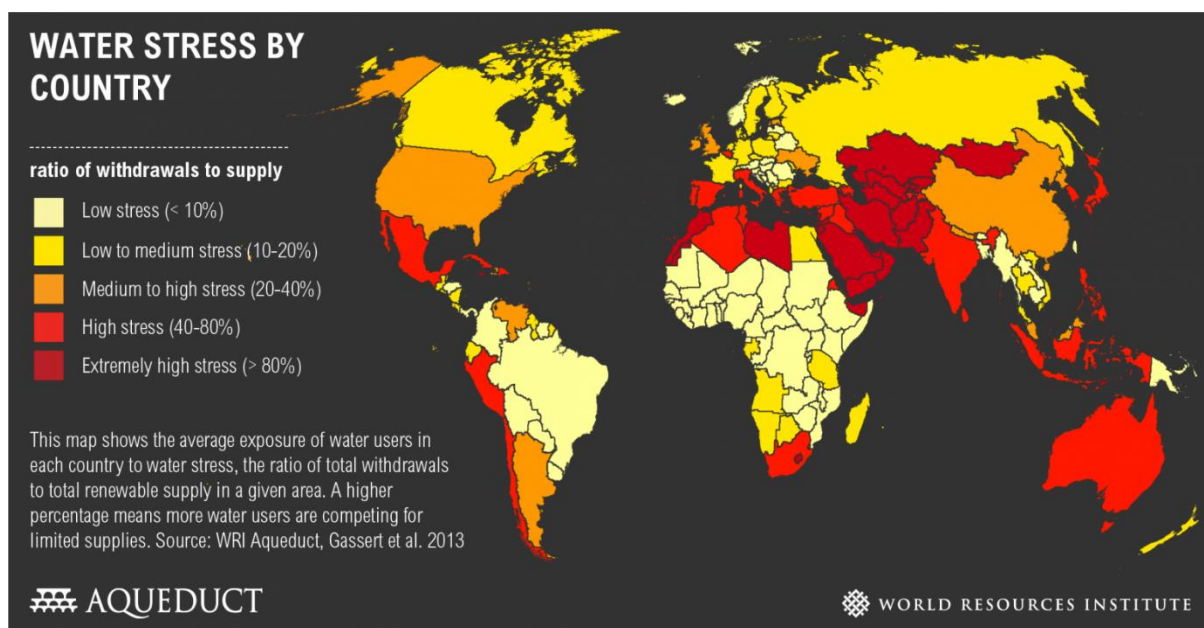


Figure S1. Water Stress by Country according to the WRI (WRI - World Resources Institute, 2019).

The African continent faces huge pressures from rapid urbanization and population growth, besides counting with regions exposed to high water stress. The continent has an important climate variability and has experienced a massive migration from rural to the urban settings - in 1950, only 1 country in Africa had a predominantly urban population, a number that has increased to 24 in 2018 and projected by the UN to reach 58 countries in 2050 (UN-DESA, 2019). This puts enormous pressure on resources, urban water systems, housing, food production and institutions, in addition to increasing competition between water users (agriculture, industries and municipalities). Furthermore, the decline of total renewable water resources per capita increases the challenge of supplying water for an increasing population (FAO, 2020).

Asia, also having experienced a rapid urbanization and a decline of water availability (FAO, 2020) have an additional challenge related to intensive economic growth and therefore, finding a balance between industrial water use and water security (Gu et al., 2017). Disparities and water hazards (ADB2016,UN) are also water security issues observed in this continent (Asian Development Bank (ADB), 2016; CRED - Centre for Research on the Epidemiology of Disasters & UNISDR - UN Office for Disaster Risk Reduction, 2015). As seen in Figure S2, China and India have a high occurrence of weather-related disasters - the majority being floods. Associated to climate change, these hazards are intensified by extensive building and changed retention capacity in cities (Arcadis, 2016). Management

strategies, such as The Sponge City Program (SCP) in China (Qi et al., 2021) have been put in place to address these water issues.

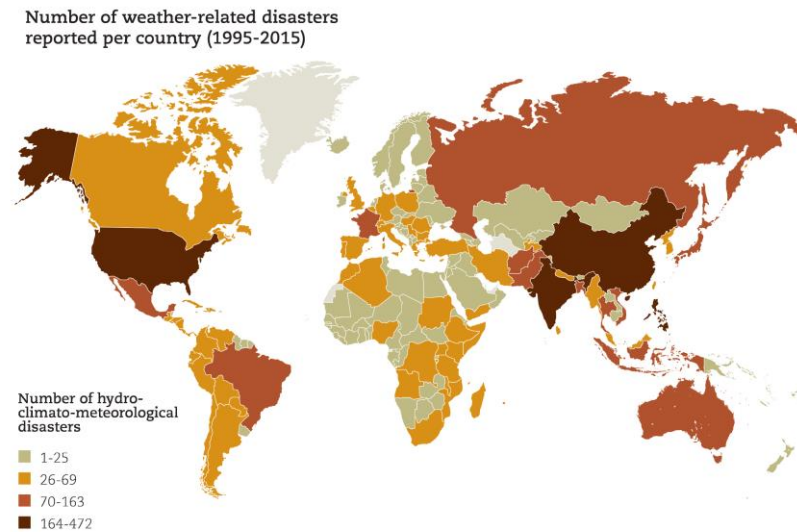


Figure S2. Weather-related disasters reported per country by CRED and UNISDR (CRED - Centre for Research on the Epidemiology of Disasters & UNISDR - UN Office for Disaster Risk Reduction, 2015).

The reduction of water availability also affects high-income countries. Projections show that specific areas of the United States could experience a 40% increase of water stress by 2040 (WRI - World Resources Institute, 2019). The US also faces water security issues in terms of vulnerability to disasters and extreme weather (CRED - Centre for Research on the Epidemiology of Disasters & UNISDR - UN Office for Disaster Risk Reduction, 2015). In California, water crisis has led to efforts on water conservation, reuse, and source diversification by the city of Los Angeles (Arcadis, 2016). Additionally, disparities in parts of the country originate water systems shortcomings and accessibility issues even in metropolitan areas (Meehan et al., 2020). Also in North America, Canada faces issues with disparity in access and infrastructure, especially with water supply to indigenous communities: statistics show approximately one-in-five communities having been in on a boil water advisory at any one time (UNESCO i-WSSM, 2019).

In Latin America, social and geographical disparities, governance, investment, climate change and extreme weather are some of the challenges faced by the region (Arcadis, 2016; Gesualdo et al., 2019). Even countries with low water stress, like Brazil, have regions where pressures are high - due to economic activities, urban density or climate - and therefore, suffer from water stress (FAO, 2020). Extreme events have also caused water shortages: in 2014, facing a water crisis, 1,485 municipalities out of the 5,561 in the State of Sao Paulo have declared a state of emergency (UNESCO i-WSSM, 2019).

Europe, although considered to lead the way in terms of water sustainability, faces water security issues related to extreme weather, changes in water availability (CRED - Centre for Research on the Epidemiology of Disasters & UNISDR - UN Office for Disaster Risk Reduction, 2015; WRI - World Resources Institute, 2019) (UN and WRI) and aging water infrastructure (Arcadis, 2016).

The diversity of water security challenges is also related to economic activities and consumption. The Water Footprint concept and tool (Water Footprint Network, 2020) give geographically explicit information that relates consumption, production, climate, and pollution. It allows to see how economic activities and consumption behaviour, for instance, influence water use: high income countries usually consume more goods and services, while in low-income countries have a larger consumption in the agricultural sector, both factors contributing to increase the water footprint of the country and the pressures on resources (Hoekstra & Chapagain, 2007).

S2 Water security definitions

Here we present some of the well-known definitions of water security:

- The UN Ministerial Declaration of The Hague on Water Security in the 21st Century describes the water security challenge as *“ensuring that...ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy and productive life and the vulnerable are protected from the risks of water-related hazards”* (World Water Council, 2000). The Declaration recognized the importance of managing risks and using targets and strategies to ensure these ends are achieved, and it highlights the growing focus on indicators of water security to track trends and inform management decisions.
- A much broader perspective on water security was offered by the Global Water Partnership (GWP) in 2000, which recognized water security *“as a common goal”*, and defined it as *“access to adequate quantities of water, of acceptable quality, for human and environmental uses”* (Global Water Partnership, 2000).
- At the fourth World Water Forum in 2006, Grey and Sadoff (Grey & Sadoff, 2007) examined the relationship between water security and economic development by highlighting the development of challenges in regions exposed to high levels of hydroclimatic variability. Water security was defined as the *“availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economics”*.
- Almost a decade ago, in 2013, the UN-Water used a dialogue process to define water security based on the multiple interests tied to it (UN-Water, 2013). The resulting working definition describes water security as *“the capacity of a population to safeguard sustainable access adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development; for ensuring protection against water-borne pollution and water-related disasters; and for preserving ecosystems in a climate of peace and political stability”*.
- The VIIIth Strategic Plan of the UNESCO Intergovernmental Hydrology Programme (2014-2021) is entirely focussed on Water Security (UNESCO, 2014). The IHP takes different scales into account and focuses on local, regional and global challenges. The strength of the IHP is that it connects water research and management to education and capacity building. The main objective is to put science into action. The VIIIth strategic plan uses the following definition for Water Security, which was formally ratified by the members of IHP intergovernmental council: *“The capacity of a population to safeguard access to adequate quantities of water of acceptable quality for sustaining human and ecosystem health on a watershed basis, and to ensure efficient protection of life and property against water related hazards: floods, landslides, land subsidence and droughts”*.
- In 2013, the *OECD* adopted a risk-based approach to water security (OECD, 2013). Water security is *“about managing water risk”* to an acceptable level across four classes of chronic and episodic hazards: shortage, inadequate quality, excess (flooding), and diminished resilience of freshwater systems. This concept of water security is the basis for the OECD framework to *“know, target and manage”* water risks in a situation of uncertainty.

Many other water security definitions can be found in the literature. Allan et al. (2018) have identified 25 unique water security definitions and carried out an in-depth analysis of themes included in them. The authors observed the evolution of themes and increasing complexity: starting with water supply themes, over the years the definitions began to include quality, human health, economic productivity, environmental aspects, hazards risk, liveability, and social value of water. According to this study, since the last decade, no new themes were observed, although the prevalence has evolved, showing an increasing attention to environmental and social aspects.

This evolution and special attention to social, cultural and economic perspectives is also observed in the progression of UNESCO's Intergovernmental Hydrological Programme (Makarigakis & Jimenez-Cisneros, 2019). The core themes of the programme have changed during the different phases, going from focusing on water resources to including societal and environmental challenges.

The is evidence of the complexity of water security, a concept that goes beyond water supply and sanitation and is closely linked to all the SDG, as illustrated by Figure S3. Broader definitions highlight this multi-dimensional quality and encourage researchers and stakeholders to consider and monitor different aspects of water security.



Figure S3. Water centric Sustainable Development Goals (Makarigakis & Jimenez-Cisneros, 2019).

Table S1. Water security aspects found in water security frameworks - extended version

Here we present the extended version of Table 2, including references for the aspects. This is not an exhaustive list of references, but a guide so readers can find actual frameworks employing these different aspects.

Dimension	Categories	Indicators/aspects
Drinking water & human well-being	Water quantity	Water availability (Aboelnga et al., 2019; Assefa et al., 2019; Carden & Armitage, 2013; Liu et al., 2018; Policy Research Initiative (Canada), 2007); adequate quantity for basic needs (Aihara et al., 2015; Brewis et al., 2020; Tsai et al., 2016), demand and consumption (Khan et al., 2020; Romero-Lankao & Gnatz, 2016; van Leeuwen et al., 2012; Yomo et al., 2019); diversity of sources (Aboelnga et al., 2019; Jensen & Wu, 2018; Shrestha et al., 2018); precipitation and water balance (Arcadis, 2016; Jia et al., 2015; van Ginkel et al., 2018); water storage (Arcadis, 2016; Ghosh et al., 2019; Vorosmarty et al., 2010); exploitation of resources (Chen & Shi, 2016; Jia et al., 2015; Zhang et al., 2019); water stress (Arcadis, 2016; Essex et al., 2020; Vorosmarty et al., 2010); and usage efficiency (van Leeuwen et al., 2012; Yin et al., 2017).
	Quality	Quality of water for human consumption (meeting standards) (Assefa et al., 2019; Khan et al., 2020; Krause, 2015; Schur, 2017); aesthetic, perception, and quality acceptability (Brewis et al., 2020; Jepson, 2014; WaterAid, 2012); water treatment practices (Milman & Short, 2008; Schur, 2017; Shrestha et al., 2018).
	Access to water services	Access to improved drinking water source (Arcadis, 2016; ARUP, 2019; Gain et al., 2016; Lautze & Manthrilake, 2012); improved sanitation (Asian Development Bank (ADB), 2016; Carden & Armitage, 2013; Essex et al., 2020; Romero-Lankao & Gnatz, 2016); piped water or water supply connection (Danilenko et al., 2014; Jensen & Wu, 2018; Liu et al., 2018); accessibility of water points (Brewis et al., 2020; Stevenson et al., 2016); affordability of services (Aboelnga et al., 2019; Koop et al., 2017; Schur, 2017); wastewater collection/sewage connection (Asian Development Bank (ADB), 2016; Jensen & Wu, 2018; Khan et al., 2020).
	Infrastructure reliability	Asset management and maintenance (Aboelnga et al., 2019; ARUP, 2019; Krause, 2015; Milman & Short, 2008); infrastructure condition/age and capacity (Iribarnegaray et al., 2012; Policy Research Initiative (Canada), 2007); reliability (complaints/ blockages/ interruptions) (Aboelnga et al., 2019; Jepson, 2014; Krause, 2015); service level (Carden & Armitage, 2013); service continuity (hours of service) (Arcadis, 2016; Shrestha et al., 2018; van Ginkel et al., 2018); water leakage, non-revenue water (Aboelnga et al., 2019; Essex et al., 2020; van Ginkel et al., 2018; van Leeuwen et al., 2012).
	Reuse/ recycling	Water/wastewater reuse (Arcadis, 2016; Dou et al., 2019; Yomo et al., 2019); energy or nutrient recovery (Essex et al., 2020; van Leeuwen et al., 2012); rainwater harvesting (Ghosh et al., 2019; Li et al., 2018); solid waste/recycling (Carden & Armitage, 2013; Essex et al., 2020).
	Hygiene and public health	Water related diseases (Arcadis, 2016; Policy Research Initiative (Canada), 2007; van Ginkel et al., 2018); incidence of diarrhoea (Aboelnga et al., 2019; Asian Development Bank (ADB), 2016; Khan et al., 2020; Romero-Lankao & Gnatz, 2016); adequacy of water for

Ecosystems	Wellbeing	housework and hygiene ; other health problems (Carden & Armitage, 2013). Emotional stress, fear, frustration (Jepson, 2014; Schur, 2017; Stevenson et al., 2016; Tsai et al., 2016); safety or dispute (Aihara et al., 2015; Jepson, 2014; Stevenson et al., 2016); deprivation or lost opportunity (Aihara et al., 2015; Brewis et al., 2020; Stevenson et al., 2016); recreational opportunities (Marttunen et al., 2019).
	Environment	Surface and groundwater water quality (Aboelnga et al., 2019; Essex et al., 2020; Norman et al., 2013; van Ginkel et al., 2018); river health (Asian Development Bank (ADB), 2016; Babel & Shinde, 2018); wastewater generated and adequacy of wastewater treatment(Krause, 2015; Shao et al., 2012; van Ginkel et al., 2018; Yin et al., 2017); biodiversity (Arcadis, 2016; Marttunen et al., 2019; Policy Research Initiative (Canada), 2007; van Leeuwen et al., 2012); environmental flows (Asian Development Bank (ADB), 2016; Lautze & Manthrilake, 2012; Vorosmarty et al., 2010); environmental protection actions (ARUP, 2019; Krause, 2015); pollutants discharge (harmful substances, pollution loading) (Chen & Shi, 2016; Jia et al., 2015; van Ginkel et al., 2018; Vorosmarty et al., 2010); soil erosion (Yin et al., 2017); wildfires; vegetation cover and land use (Aboelnga et al., 2019; Arcadis, 2016; Babel & Shinde, 2018).
	Sustainability	Energy use/efficiency(Aboelnga et al., 2019; Krause, 2015; van Leeuwen et al., 2012); renewable energy (Essex et al., 2020; Marttunen et al., 2019); sustainable natural resources use(Carden & Armitage, 2013; Marttunen et al., 2019); sustainable water use (ARUP, 2019; Essex et al., 2020; van Ginkel et al., 2018); water sensitive urban design(ARUP, 2019; Li et al., 2018).
	Water-related hazards	Floods (frequency(Babel & Shinde, 2018; Gain et al., 2016; van Ginkel et al., 2018), affected area (Aboelnga et al., 2019; Babel & Shinde, 2018) and population (Babel & Shinde, 2018; Liu et al., 2018), hazard and vulnerability (Asian Development Bank (ADB), 2016; Essex et al., 2020; van Ginkel et al., 2018), protection infrastructure(Dou et al., 2019; van Ginkel et al., 2018)); droughts (frequency/vulnerability/area affected)(Aboelnga et al., 2019; Asian Development Bank (ADB), 2016; Gesualdo et al., 2019); economic loss (Chen & Shi, 2016; Jensen & Wu, 2018; Liu et al., 2018); landslides; prevention, preparedness, and response(ARUP, 2019; Chen & Shi, 2016; Li et al., 2018; Marttunen et al., 2019); water pollution accidents(Jensen & Wu, 2018; Li et al., 2018; Su et al., 2019; Yin et al., 2017).
Water hazards & Climate change	Climate change	Climate change response (Carden & Armitage, 2013; Essex et al., 2020; van Leeuwen et al., 2012); greenhouse gas emissions (Aboelnga et al., 2019; Dou et al., 2019; Essex et al., 2020; Krause, 2015); salination and seawater intrusion; temperature (Aboelnga et al., 2019; Yomo et al., 2019).
	Economic activities	Water for agriculture(Asian Development Bank (ADB), 2016; Lautze & Manthrilake, 2012; Vorosmarty et al., 2010), manufacturing and commerce (Asian Development Bank (ADB), 2016; Carden & Armitage, 2013; Chen & Shi, 2016; Jia et al., 2015; van Ginkel et al., 2018); energy production; broad economic development; (Asian Development Bank (ADB), 2016); water-related business opportunities; food production and demand(Xiao et al., 2008); water footprint (Marttunen et al., 2019);
Economic Activities & Development		

	van Ginkel et al., 2018; van Leeuwen et al., 2012); water use/GDP or GDP/water use (Babel & Shinde, 2018; Dou et al., 2019; Jia et al., 2015; Khan et al., 2020; Yomo et al., 2019).
Governance	Institutional organization and capacity (Araral & Yu, 2010; Carden & Armitage, 2013; Milman & Short, 2008; OECD, 2018; van Ginkel et al., 2018); accountability and corporate governance (Araral & Yu, 2010; Khan et al., 2020; Koop et al., 2017; van Ginkel et al., 2018); data availability (Araral & Yu, 2010; OECD, 2018; van Ginkel et al., 2018), multi-level, and multi-stakeholder participation/engagement (Araral & Yu, 2010; ARUP, 2019; Iribarnegaray, 2012; Koop et al., 2017; van Ginkel et al., 2018; van Leeuwen et al., 2012); communication and transparency (ARUP, 2019; Koop et al., 2017; Krause, 2015); investment/funding and financial management (Aboelnga et al., 2019; Araral & Yu, 2010; Carden & Armitage, 2013; Essex et al., 2020; Khan et al., 2020; Krause, 2015; Milman & Short, 2008; OECD, 2018); legal and regulatory aspects (Araral & Yu, 2010; Jensen & Wu, 2018; Koop et al., 2017; Romero-Lankao & Gnatz, 2016); science, knowledge, and innovation (Araral & Yu, 2010; ARUP, 2019; Koop et al., 2017; OECD, 2018); strategic planning (Babel & Shinde, 2018; Jensen & Wu, 2018; Milman & Short, 2008; van Leeuwen et al., 2012); transboundary and international collaboration (Aboelnga et al., 2019; Essex et al., 2020; Gain et al., 2016; Lautze & Manthrithilake, 2012; Marttunen et al., 2019; Romero-Lankao & Gnatz, 2016; van Leeuwen et al., 2012).
Socio-economic aspects	Education and awareness (Carden & Armitage, 2013; Khan et al., 2020; OECD, 2018; Policy Research Initiative (Canada), 2007); GDP (Chen & Shi, 2016; Li et al., 2019; van Ginkel et al., 2018; Yomo et al., 2019); income/unemployment rate (Carden & Armitage, 2013; Chen & Shi, 2016; Romero-Lankao & Gnatz, 2016; Wutich & Ragsdale, 2008); informal dwellings (Carden & Armitage, 2013; van Ginkel et al., 2018); population density (Li et al., 2019; Romero-Lankao & Gnatz, 2016; Su et al., 2019; Yin et al., 2017; Yomo et al., 2019); social and cultural aspects(Policy Research Initiative (Canada), 2007; Wutich & Ragsdale, 2008); urbanization rate (Chen & Shi, 2016; Yin et al., 2017).
