Appendix 1: Quantification of urban water supply security

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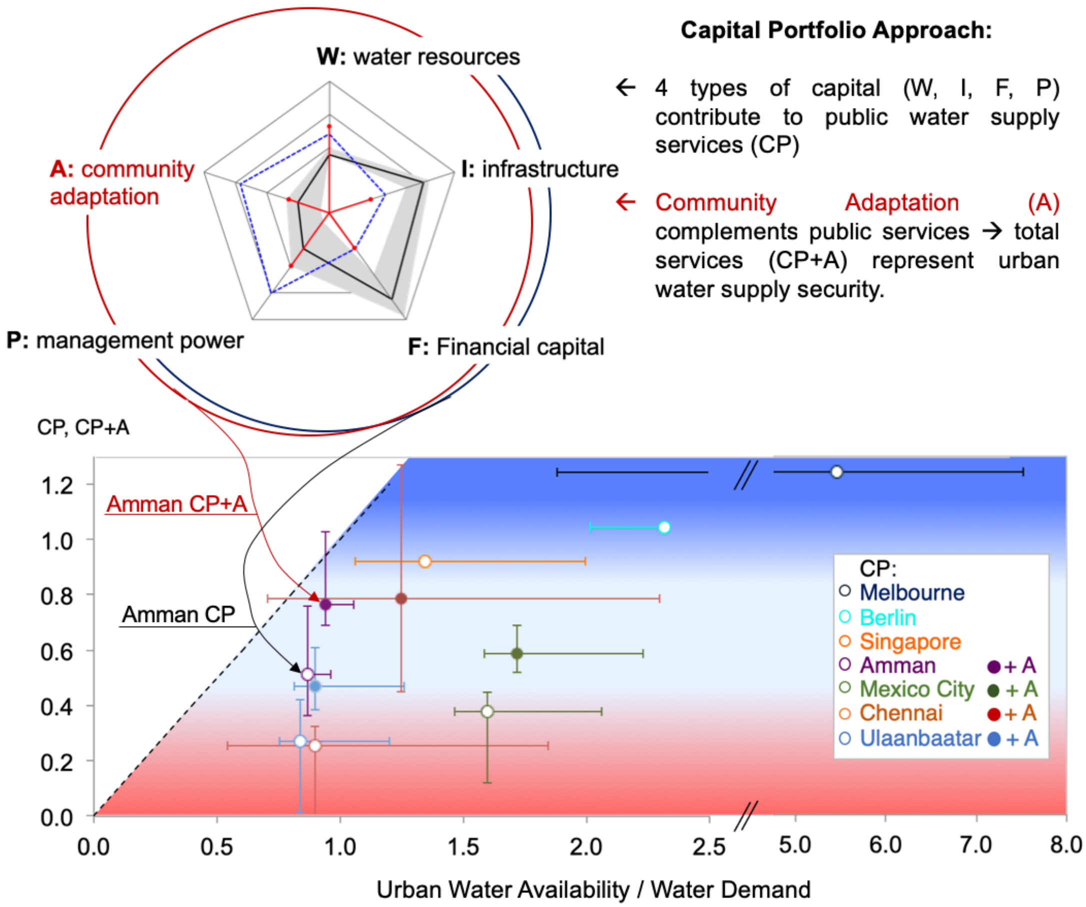
Quantifying Urban Water Supply Security Under Global Change

Krueger, E.[1,2,*], Rao, PSC.[2,3], Borchardt, D.[1]
1: Helmholtz Centre for Environmental Research – UFZ, Department of Aquatic Ecosystem Analysis, Permoserstr. 15, 04318 Leipzig, Germany
2: Lyles School of Civil Engineering, 550 Stadium Mall Drive, Purdue University, West Lafayette, Indiana 47907, USA
3: Agronomy Department, Purdue University, West Lafayette, Indiana 47907, USA
* Corresponding Author

Urban water supply security is commonly measured in terms of per capita water availability at the city level. However, the actual services that citizens receive are influenced by several components, including (1) a city's access to water, (2) infrastructure for its treatment, storage and distribution, (3) financial capital for building and maintaining infrastructure, and (4) management power for regulating and operating the water system. These four types of "capital" are required for the provision of public water supply services. A fifth capital “community adaptation” is needed when public services are insufficient. Here, we develop and test an integrated framework for the quantification of urban water supply security based on these five capitals. “Security” involves three dimensions: 1) the level of system function (i.e., supply services); 2) risks to these services; and 3) robustness of system functioning. We apply this Capital Portfolio Approach (CPA) to seven urban case studies selected from a wide range of hydro-climatic and socio-economic regions on four continents. Detailed data on urban water infrastructure and services were collected in two cities, and key stakeholder interviews and household surveys were conducted in one city. Additional cities were assessed based on publicly available utility and globally available datasets. We find that in cities with high levels of public services, adaptive capacity remains inactive, while cities with high levels of water insecurity rely on community adaptation for self-provision of services. Inequality in the capacity to adapt leads to variable levels of urban water security and the vulnerability of the urban poor. Results demonstrate the applicability of the presented framework for the assessment of individual urban water systems, as well as for cross-city comparison of any type of cities. We discuss implications for policy and decision-making.

Keywords: Capital Portfolio Approach (CPA), adaptive capacity, infrastructure, institutions, service management

Graphical Abstract:



Highlights:

- We integrate natural, engineered, and human elements to systematically quantify urban water security.
- We combine local (urban scale) assessments with a comparison across global cities to identify different types of urban water security.
- The approach provides a framework to assess urban water security and management options.

1 Introduction

In spite of significant investments into the access of additional resources and the construction of infrastructure, large numbers of cities around the world are unable to reliably supply all citizens with adequate water services (Wutich et al., 2017). A growing, global urban population, degrading ecosystems and more variable weather and climate with consequences on water availability have moved urban water security into the focus of managers and researchers alike (Cosgrove and Loucks, 2015; Floerke et al., 2018; Hoekstra et al., 2018; Jenerette and Larsen, 2006; McDonald et al., 2014; Padowski et al., 2016; Padowski and Jawitz, 2012).

Global assessments of urban water supply security quantify the average per capita water availability (Damkjaer and Taylor, 2017; Floerke et al., 2018; Jenerette and Larsen, 2006; McDonald et al., 2014, 2011; Padowski and Jawitz, 2012). Based on a comparative assessment of 108 cities in Africa and the US, Padowski et al. (Padowski et al., 2016) suggest that urban water security results from a combination of local hydrological conditions and management institutions in place that are capable of developing infrastructure for accessing regional water resources as needed. 7% of investigated cities remain insecure, due to minimal ability to access local and/or imported water. Floerke et al. (Floerke et al., 2018) present an analysis of 482 of the largest cities worldwide regarding water security resulting from competitive uses among different sectors. Their results indicate that 27% of cities will be facing water security issues due to surface water deficits by 2050, while an additional 19%, which are dependent on surface water transfers, will be facing competitive conflicts with agricultural water use.

Besides these water availability constraints, case study assessments reveal that several causes impact urban water security, including the lack of water resources, water quality impairments, infrastructure and governance issues, as well as the lack of community adaptive capacity (Eakin et al., 2016; Jensen and Wu, 2018; Srinivasan et al., 2010a; Wutich et al., 2017). Approaches for addressing urban water security issues abound, and have been reviewed in several articles (Damkjaer and Taylor, 2017; Garrick and Hall, 2014; Hoekstra et al., 2018), showing the breadth of the field, which includes disciplinary, problem-oriented or risk-based, goal-oriented, governance oriented and integrated approaches to urban water security. This reflects the complexity of processes contributing to urban water security and interacting system elements operating at a wide range of scales, which limit the possibility of direct measurement (Jensen and Wu, 2018) and parameterization typical of systems modeling approaches. Due to these limitations, the development of urban water security indicators is a thriving field of research, which allow aggregation of multiple system elements (Damkjaer and Taylor, 2017; Fischer et al., 2015; Hinkel, 2011; Marques et al., 2015; Milman and Short, 2008; Sharifi and Yamagata, 2016; Spiller, 2016; van Leeuwen et al., 2012). However, the apparent ease of defining and applying indicators bears a certain risk of misuse and mis-interpretation, and requires careful development, application, and empirical support of salient indicators

(Garrick and Hall, 2014; e.g., Hoekstra et al., 2018; Jensen and Wu, 2018). In their recent review, Hoekstra et al. conclude that consensus on the definition of urban water security, as well as a method for its quantification are lacking (Hoekstra et al., 2018). The authors propose a systems perspective using a pressure-state-impact-response framework for assessing urban water security, in which the four elements can be summarized as: Pressures = risks, state = state of water resources and infrastructure, impacts = services resulting from pressures and state, response = response by managers and the community to inadequate piped water supply (Hoekstra et al., 2018). We use a similar approach here and combine it with an indicator-based approach, as elaborated below.

Urban water supply security is defined here as the performance of a system function: the services that citizens receive, including access, safety, reliability, continuity and affordability. In well-developed cities, public providers cover these services. However, where public services are insufficient, the community is forced to cope and adapt to these insufficiencies. We therefore propose that urban water supply security (UWS) results from a combination of public services and community adaptation measures. Public services require the availability of four "capitals" and their robustness to potential risks: 1) water resources ("natural capital"), 2) infrastructure ("physical capital") and 3) financial capital, as well as 4) governance institutions ("political capital") managing the former three. The fifth capital 5) community adaptation ("social capital") in response to insufficient services can complement or replace public water services. The concept of capitals required for sustaining urban livelihood functions is adapted from the Sustainable Livelihood Framework proposed by the Department for International Development (DfID, 1999). The notion of "capitals" available to individuals for improving their livelihoods relates back to Bourdieu's "The Forms of Capital" (Bourdieu, 1986), and has since been adapted and applied to different systems. The three dimensions (availability, robustness and risk) of the five capitals can be considered a further development and merging of the pressure-state-impact-response framework proposed by Hoekstra et al. (Hoekstra et al., 2018) and the Sustainable Livelihood Framework.

Risk is a combination of hazard, exposure and vulnerability (Garrick and Hall, 2014), which plays out differently in various urban contexts (Hoekstra et al., 2018). In risk assessment, risk probability is calculated based on a combination of past hazard occurrence and spatial exposure and vulnerability maps. However, given the non-stationarity not only of hydro-climatic, but also of socio-political conditions, urbanization dynamics, as well as heterogeneous and limited empirical data for quantifying risk, robust approaches to risk assessment are needed (Garrick and Hall, 2014). Robustness is defined as the ability to buffer shocks and the insensitivity to disturbances that result from risks, so that system performance can be maintained in spite of variability in system components (Carlson and Doyle, 2002; Homayounfar et al., 2018).

Our goal is to present a quantitative approach of UWS that is applicable to all cities around the world. We focus on urban water supply security in terms of the state of services, potential risks and robustness, acknowledging the complexity of urban water systems and the various ways in which they can fail. The approach is applied to seven case study cities representing a broad range of conditions, including different climates, cultures, sizes, socio-economic conditions, and historical contexts. We use data on urban water infrastructure and services collected from utilities and field research in two cities (Amman, Jordan; Ulaanbaatar, Mongolia), key stakeholder interviews and a household survey conducted in Amman, complemented by published datasets for these and the remaining case study cities. A brief overview of the seven cities is given below, followed by a summary of the proposed method, results of its application and a discussion of the implications. Details of the method and supporting data are provided in the *Supplementary Information (SI).*

1.1 Case Studies

Capital city of one of the most water scarce countries in the world, **Amman (Jordan)**, is faced with a rapidly growing population driven by repeated waves of refugees fleeing from conflict and war in neighboring countries. Large-scale water imports and urban infrastructure investments allow urban managers to provide citizens with relatively high standards of supply, but this water provision is energy-intensive and costly. Leakage losses are high and supply is intermittent, delivered on 2.5 days per week on average. Households store water in rooftop tanks and, those who can afford to buy additional water from tanker trucks. Water quality concerns urge citizens to treat water before drinking (own data), and sanitation infrastructure covers only 80% of households (Miyahuna, 2014).

Public water supply in **Chennai (India)** covers around 65% of demand, while the remainder is covered by the private market and self-supply from wells and other sources (Venkatachalam, 2015). A drought in 2003/2004 led to the complete shut-off of piped supply (Srinivasan, 2008). Water revenues cover merely 50% of expenditures, and 30% of operation and maintenance costs are government-subsidized. 28% of Chennai's population officially lives in slums and households have adopted mixed strategies to cope with deficient services, as public supplies vary in terms of cost, delivery frequency, volumes, and water quality (Chandramouli, 2003; Srinivasan et al., 2010b; Venkatachalam, 2015).

Officially, around 80% of households in the Greater **Mexico City** area are connected to the piped supply system, of which around half receive water continuously (Lankao and Parsons, 2010). Severe land subsidence due to over-pumping of local groundwater, as well as recurring Earthquakes cause damage to underground water pipes and leakage losses of 30% (Tellman et al., 2018; Tortajada, 2008). Sanitary infrastructure is lacking in most parts of the city, and only 10% of wastewater is treated (Tortajada, 2008; Tortajada and Castelan, 2003). Frequent flooding necessitates pumping of storm- and wastewater away from the urban basin, and leads to high prevalence of acute diarrheal diseases (Lankao and Parsons, 2010). Unplanned growth, understaffing, financial insufficiencies and dilapidation of the pipe network are burdening urban water governance. Inequality of access and supply has led to violence, and high fractions of income spent on water (Eakin et al., 2016; Tortajada, 2008). Water imported from outside the urban boundaries has caused conflict with rural populations (Watts, 2015).

The coldest capital city in the world, **Ulaanbaatar (Mongolia)**, has experienced rapid population growth over the past decades, as the country's formally nomadic people are settling in urban areas. 59% of the city's inhabitants live in informal settlements, which lack basic infrastructure, such as water supply and sanitation, and dwellers cover their demand by collecting water in small containers filled at water kiosks, and by drilling wells, often in proximity to unlined pit-latrines, which causes a high risk of water contamination (Myagmarsuren et al., 2015). Average annual discharge of the Tuul River, the city's main water source, has halved in the period 2000-2010 compared to 1972-1991 (JICA, 2013), and the river has been reported to run dry during late spring in recent years. Infrastructure construction and maintenance is particularly demanding due to temperatures remaining below freezing during the majority of the year. Existing water infrastructure dates back to the socialist era, and is in dire need of repair and expansion.

In **Singapore, Melbourne (Australia)** and **Berlin (Germany)** water is provided continuously to all citizens at drinking water quality. Revenues cover operation and maintenance costs, and an income surplus of approximately 10% annually, as well as government support provides reserve funds and financial capital for infrastructure expansion and technological advancements (BWB, 2016; MelbourneWater, 2017; Public Utilities Board (PUB), 2017). These cities' utilities jointly manage water supply and drainage, as well as energy production (from hydropower and/or wastewater treatment plants).

In the past, **Melbourne** followed a supply-oriented strategy and developed large storage capacities in surface reservoirs, and following a 13-year drought (1997-2010) invested in desalination plants. More recently the city has entered a path towards becoming a water-sensitive city, with demand-management and participatory approaches to urban water management (Brown et al., 2009; Ferguson et al., 2014).

Berlin's water catchment areas include former mining and industrial areas, requiring careful monitoring of water quality (IGB, 2016). Governance (from public to private and back to public utility ownership), demographic and demand changes require a highly adaptive management (Monstadt and Schlippenbach, 2005; Passadakis, 2006).

Singapore's rapid rise to become a global hub for water innovation and technology coincides with limited access to water resources due to constrained land area, and the need for resource imports, including real and virtual water (Hausmann et al., 2013; Khoo, 2009).

Table 1 provides additional information on the case study cities, which were relevant for selection. Details of the data used, case study descriptions containing additional information and supporting literature is provided in the *SI*.

Table 1: Overview of urban water case studies. GW=groundwater, SW=surface water, WQ=water quality. Population in Mexico City for city proper and MA=Metropolitan Area. GDP is per capita national average (data: World Bank). Climate according to Koeppen-Geiger classification; P=precipitation and T=temperature are mean annual. Service regime shows continuity of supply in days per week (days/7days).

City (population, GDP)	**climate P T**	**water sources**	**public supply/ demand (lpcd)**	**service regime**	**challenges**	**innovations**
Amman (4.1M, US$ 4,130)	Csa 350 mmy^{-1} 16.6˚C	44% GW, 44% SW, 12% local springs & wells; 30% of water is imported across boundaries	91.6/140	intermittent (2.5/7), WQ impairments	water scarcity, demand growth, dependence on water imports, financial deficit, water leakage	plans to import desalinated water from Red Sea
Berlin (3.6M, 44,470 US$)	Cfb 570 mmy^{-1} 9.1˚C	60% GW, 29% riverbank filtrate, 11% managed aquifer recharge	110/110	continuous (7/7)	water quality	switch from public to private and back to public utility
Chennai (5.5M, US$ 1,942)	Aw 1197 mmy^{-1} 28.6˚C	50% SW, 32% desalinated water, 17% GW (upper boundary)	84/154	intermittent (variable), WQ impairments, safety issues	dilapidated infrastructure, droughts, urban-rural competition for resources, unequal supply to citizens	managed aquifer recharge ("rainwater harvesting"), desalination
Melbourne (4.1M, US$ 57,800)	Cfb 666 mmy^{-1} 14.8˚C	100% SW (+ desalinated & recycled water as needed)	161/161	continuous (7/7)	prolonged droughts, floods	waste water recycling, greywater reuse, desalination, water-sensitive urban design
Mexico City (city: 8.9M, MA: 23.9M; US$ 8,910)	Cwb 625 mmy^{-1} 15.9˚C	66% local SW & GW; 33% imported SW	202/230	intermittent (variable), WQ impairments, safety issues	dilapidated infrastructure, land subsidence from overpumping, unequal supply to citizens, urban-rural competition for resources	focus on supply-side management; citizens turn to bottled water
Singapore (5.6M, US$ 57,714)	Af 2378 mmy^{-1} 26.8˚C	40% local SW & GW, 30% imported SW, 20% reclaimed, 10% desalinated water	150/150	continuous (7/7)	limited land & water resources, dependence on water imports	local source water management, reclamation ("NEWater") & desalination
Ulaanbaatar (1.4M, US$ 3,717)	Bsk 256 mmy^{-1} -0.7˚C	93% SW (riverbank filtrate); 7% local GW	138/166	41% continuous, 59% from water kiosks (no house connection)	population growth, lack of water infrastructure (distribution network, sanitation, etc.), vulnerable water sources, financial deficit	Efforts on the integration of the water-energy nexus

2 The Capital Portfolio Approach

The Capital Portfolio Approach (CPA) proposed here combines two complementary service components: 1) Public services provided by the city through a formal organization (e.g., public water utility) and 2) self-services by the community (adaptive measures and coping strategies), which replace service *not* delivered by the public utility.

Four types of capital are required for public water supply services, and one, "social capital" (Community Adaptation, A), complements or replaces insufficient public services. In the literature, capital can refer to either a certain capacity (stock or input) or a functional performance (flow or output). Here, the quantification of the capitals focuses on the latter. Each of the five capitals is quantified in three dimensions: its availability, robustness, and risk. Quantification of each capital dimension is achieved by aggregating multiple attributes using either additive aggregation (arithmetic mean) or mixed additive and multiplicative aggregation (see *SI* for details). A detailed overview of adequate indicator aggregation methods is discussed in Langhans et al. (Langhans et al., 2014). Capitals are normalized to represent fractions of standard "demand", which corresponds to the amount of capital (per capita) required for providing full services to all citizens. Each capital takes a value between 0-1; capitals = 1 indicates availability as required for full service performance. Availability > 1 indicates "excess" availability of capitals, such as surpluses of water resources during years of relative precipitation abundance, which can be stored for periods of drought. The five capitals comprise the following:

1) Water resources (W; "natural capital") accessed by the city, including the total volume of naturally available, captured, reused, desalinated water, etc.

2) Infrastructure (I; "physical capital") to store, treat, and distribute W to all customers at drinking water quality, i.e. including delivery to each household. It includes the house connection rate to the public water distribution system, water leakage losses and a water quality coefficient.

3) Management power (M; "political capital") exerted by the urban water governance system with the ability to smoothly operate and maintain water supply services (based on institutional efficiency, accountability and regulatory complexity). M is quantified from a scoring system of twelve binary metrics which are chosen from a range of metrics proposed by (Padowski et al., 2016) and critical management criteria identified during key stakeholder interviews conducted for this study (Amman and Ulaanbaatar), as well as governance indicators identified in the literature (Akhmouch and Correia, 2016; Araral and Yu, 2013; Cook and Bakker, 2012; Grey et al., 2013; Gupta et al., 2013; Marlow et al., 2013).

4) Financial capital (F) to build, operate and maintain the water system measured as the ratio of water sector income and expenditures, as well as additional financial capital needed for expanding I, in case not all customers are adequately connected to the public system.

Following a hierarchical aggregation procedure, these four capitals are then combined to an aggregate measure, the capital portfolio required for public services (CP_{public}={W,I,F,P}). Different aggregation methods were tested and compared to empirical data and information on water supply services. We use the unweighted harmonic mean as the aggregation method at this level to account for the need of "balance" among the four capitals (low availability of one capital has a relatively large impact on the aggregate), as well as the one-out, all-out principle, acknowledging that the system cannot function, if one of the four capitals equals zero (Langhans et al., 2014). We refrain from adding weights, as research quantifying the relative importance of the four capitals is lacking.

Public services are complemented or replaced by community adaptation:

Community Adaptation (A, "social capital") refers to measures taken by citizens in response to insufficient public services. Adaptation measures include acquiring additional water resources from alternative sources (e.g., delivered by water trucks, at water kiosks, or bought from stores; private wells, rivers or harvested rainwater), installation of storage capacity in the house, treating water to make it safe to drink, and sharing water among neighbors. Availability of adaptive capacity allows the community to replace deficits in public services through community adaptation. However, this capacity remains latent, if services are delivered as demanded. Therefore, instead of measuring the capacity to adapt (which can be active or inactive), we consider actual community adaptation (active) in response to insufficient services. *A* includes a volumetric component (additional water resources accessed), a water quality component (need for water treatment for drinking purposes), and a component that represents the time and effort required for dealing with rationed (intermittent) or unreliable water delivery ("supply gap").

Robustness refers to the ability to absorb shocks and disturbances (Carlson and Doyle, 2002), and includes aspects such as diversity, anticipation of shocks and preparedness to deal with disturbances. Following a similar process to the quantification of capital availability, robustness is assessed for each of the five capitals using scoring systems that produce values between 0-1 (see *SI*).

Risks can result from chronic (high frequency, low magnitude) or acute shocks (low frequency, high magnitude) (Garrick and Hall, 2014). An example of a chronic risk is the health risk posed by potential contamination of drinking water through leaking pipes. An example of an acute risk is the destruction of infrastructure and loss of services posed by flood events and earthquakes. We use a simple approach that assigns binary scores to a range of hazards based on past experience or likely (possible) future occurrence and the vulnerability of the five capitals in each city.

The five capitals combine to total services (CP_{total} = CP_{public} + A), robustness of services (RP_{public}={W_R, I_R, F_R, P_R, A_R}), and risk (Risk={R_W, R_I, R_F, R_P, R_A}). We assume additive aggregation to CP_{total} being the most appropriate method to account for substitutability of public and self-services. Details on the quantification of the five capitals (W, I, F, P, A), robustness and risk are provided in the *SI*. The concept is illustrated in **Figure 1**.

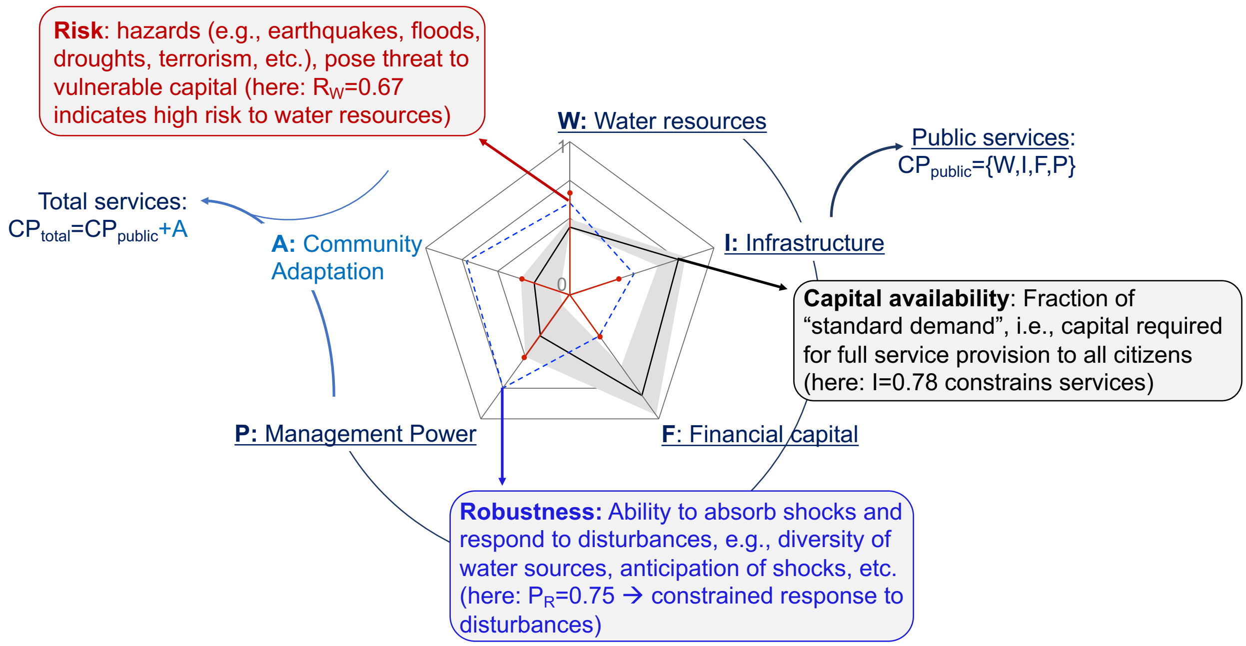


Figure 1: Capital Portfolio Approach (CPA).

3 Results

Results of the quantification of UWS using the CPA for the seven cities are summarized in **Figure 2**. Black lines are capital availabilities with uncertainty bounds (shaded areas) resulting from variability over time (all cities: W, F, I; and A for Chennai), and uncertainty in the estimation of capital values (all cities: P; and A for Ulaanbaatar, Mexico City, Amman). Dashed lines indicate capital robustness, and red lines represent risks to each of the capitals. Ulaanbaatar has low availability and robustness, and high levels of risk for all five capitals. For Chennai the picture is similar, but community adaptation is significantly higher than in Ulaanbaatar, as many citizens have private wells or other access to additional water resources. Amman and Mexico City have intermediate levels of capital availability and robustness, but the distribution of values between among capitals deviate (robustness of A and P are much higher than availability values). For P this means that, although their institutions are not strongly developed for regular operation, they have relatively high ability to respond to emergency situations when needed. For A it means that, on average, the community is not using its full capacity to adapt, because the level of services is acceptable at most times, but citizens have support structures in place, in case adaptation is needed. Mexico City has excess availability of water resources (W>1), however, low *I* indicates that this water is unequally distributed, contaminated and partly lost through leakage. Low *F* and *P* indicate that money and institutional capacity for improving the situation is unavailable. In contrast, while water resource availability is low in Amman, its infrastructure is highly developed, and although management power is not strongly developed, financial capital is available from a mix of water revenues, funding from international donors and investors, as well as government subsidies. In Singapore, Berlin and Melbourne, risks are low, capital availability and robustness are high, and A=0, which means that adaptive capacity is inactive, as public services cover demand (W, I, F, P ≈ 1). Large storage capacity and additional desalination plants lead to surplus water resources when there is no drought in Melbourne. Robustness of *F* is intermediate for Singapore and Berlin, which results from the fact that both cities depend on energy imports, and are therefore dependent on global fluctuation of energy prices for maintaining services. See *SI* for more details.

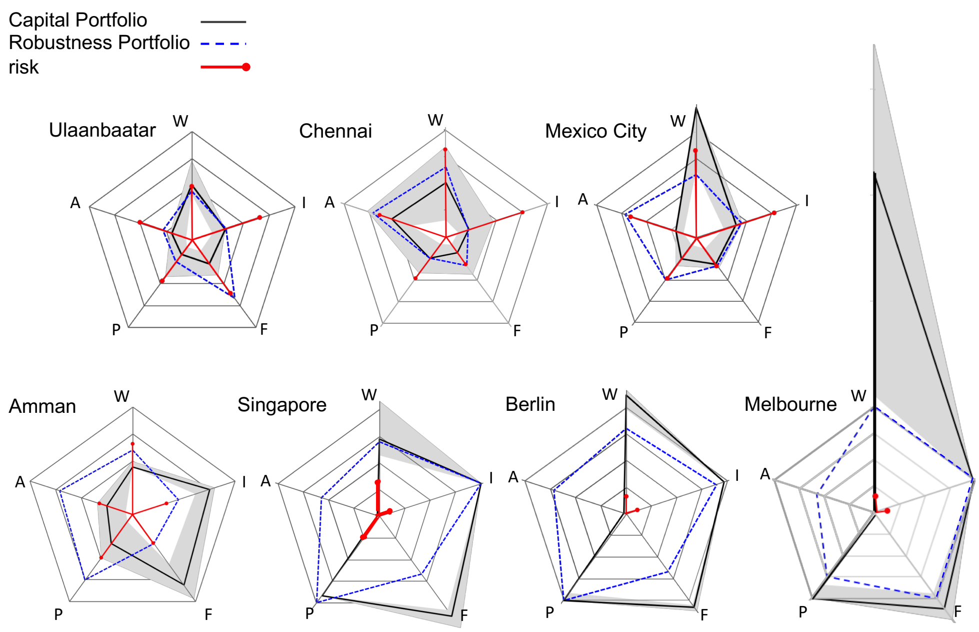


Figure 2: Capital portfolios of seven case study cities. Axes are normalized to security thresholds ("demand"=amount required for full service delivery per capita) and take values between 0-1, unless there is surplus for W and F above security requirements. The overshoot in W for Melbourne results from excess storage developed to avert shortages during drought and to anticipate increased demands.

3.1 Cross-City Comparison

Aggregation of the capitals for public services (CP_{public}) and total services ($CP_{total}=CP_{public}+A$), together with the robustness (RP) and risk metrics provide proxy measures of urban water supply security. Comparison of the composite metrics across cities is shown in **Figure 3,** where CP is represented by blue pie charts**.** $CP_{public}\approx 1$ for Melbourne, Berlin and Singapore. For Amman, Mexico City, Chennai and Ulaanbaatar, A (light blue) complements public services (dark blue). However, deficits remain ($CP_{total}<1$), indicating the deficit in public water services, and constraints in community adaptive capacity. RP is plotted in turquoise and risk (red) resulting from different risks with potential for damage to each of the five capitals. As Fig. 3 illustrates, increased CP and RP correlate with reduced risk, and result in higher water security (Garrick and Hall, 2014).

Grey circles in Fig. 3 allow a comparison of the CPA method for quantifying UWS with more common approaches based on average volumetric water availability: Grey circles labeled UWA/D_W show average urban water availability at the city level (UWA) relative to average volumetric water demand (D_W), with dark grey (W_{extra}/D_W) showing additional water resources accessed by the community through informal sources, complementing public water availability. Urban water security regarded from the perspective of city-scale UWA/D_W, is relatively high in all cities under regular circumstances (i.e., in the absence of drought and/or competition among sectors; compare to (Floerke et al., 2018)). Excess water availability is illustrated by the large grey circles for Melbourne and Berlin, as well as Mexico City. In Chennai, the apparent "excess" is produced by adding W_{extra}, accessed by the community, which could be a result of both temporal as well as spatial variability in water availability. To calculate public water *supply* (S_W) leaked water is subtracted from UWA/D_W and is capped at D_W (i.e., $S_W \leq 1$). Intra-urban infrastructure constraints (i.e., connection rate, leakage, water quality impairments), intermittence and other service constraints are considered in the quantification of CP (i.e., services). For example, all cities achieve volumetric urban average at minimum of UWA/D_W (min) = 85% (Amman) and S_W (min) = 55% (Chennai). However, water supply services are as low as CP = 25% and 27% for Chennai and Ulaanbaatar, and including self-services (CP+A) = 78% and 47% for Chennai and Ulaanbaatar, respectively.

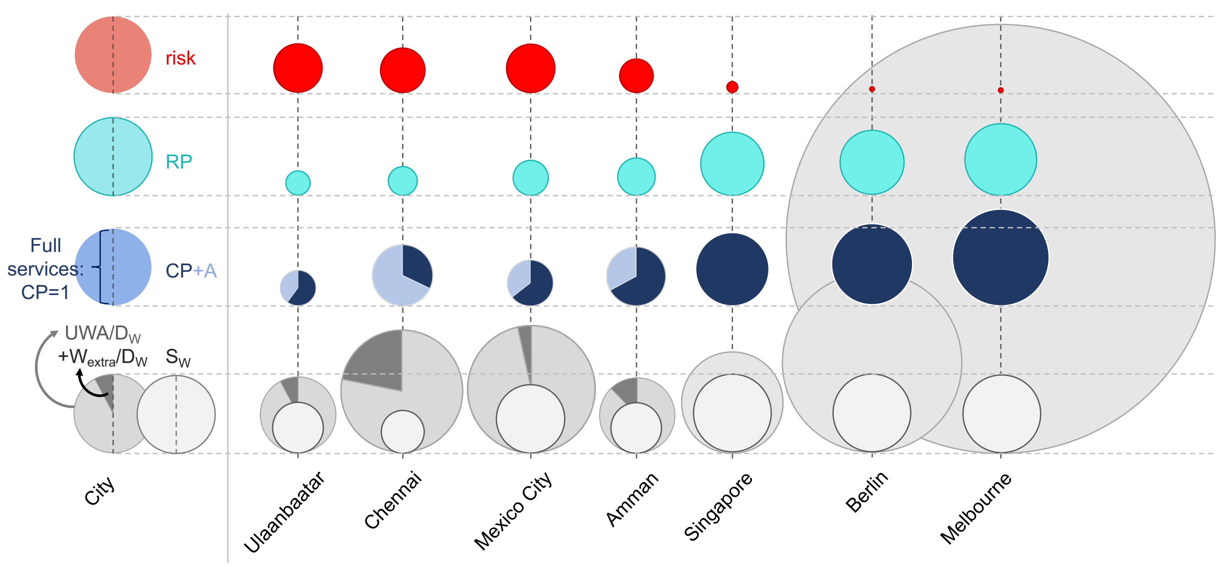


Figure 3: Comparison of urban water supply security measures across cities. Melbourne's excess water availability is indicated by the large UWA/D_W ratio (grey circle). Circles sizes in the "legend" on the left equal 1, indicating the security threshold for all but risk. Risk = 1 is maximum risk potential.

In **Figure 4** values of CP (CP+A) are plotted against UWA/D_W ((UWA+ W_{extra})/D_W). The sub-linear relationship of the two metrics indicates that the latter ratio, often used as an estimate of urban water security, overestimates urban water security, as it does not account for distributional and service quality issues. The difference between public services (CP_{public} = CP, circles) and total services (CP_{total} = CP+A; dots) illustrates the role of community adaptation in achieving or maintaining urban water supply security (e.g., private water markets providing additional water resources, household coping strategies, such as storage and water treatment at the household level). Background color shading highlight cities with low CP (+A) as water insecure (red), while a high CP (+A) indicates water security (blue). Intermediate CP (+A) indicates the transition zone.

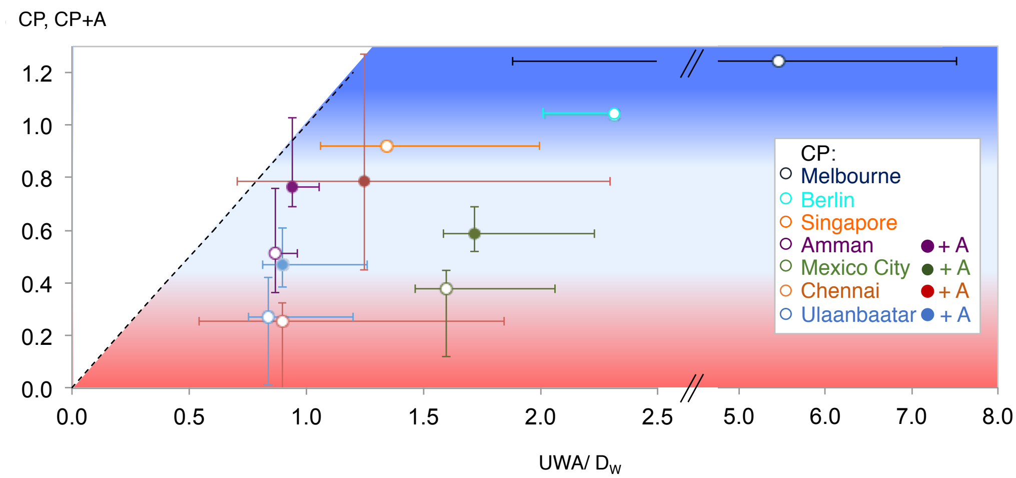


Figure 4: Comparison of two water security metrics for seven global cities. Circles = public services (CP and UWA/D_W); dots = total services (CP+A and (UWA+W_{extra})/D_W). Error bars are ranges around the mean indicating inter-annual variability and data uncertainty.

Figures 3 and 4 illustrate three points:

1) If we accept CP(+A) to be a more integrated and informative measure of urban water supply security, UWA/D_W systematically overestimates security, and is somewhat meaningless for assessing UWS, as the lack of infrastructure, finances and management power can repeal the advantage of high water availability (see Amman having relatively low UWA/D_W but relatively high CP+A and the inverse being true for Mexico City);

2) The role of community adaptation becomes evident by comparing data for public services (CP) and total services (CP+A). In Chennai, community adaptation has a higher contribution to urban water supply security than public services. In Ulaanbaatar, the capacity for adaptation in the community is lower, however still significant.

3) Error bars indicate the variability around the mean and data uncertainty, which is significantly higher for UWA/D_W than for CP(+A), as services buffer variability in (natural) water availability.

4 Discussion

The combination of natural, human, financial and engineered elements (here: the five capitals) determines whether a city can achieve or maintain water supply security. Two essential components of urban water security are 1) *public services* provided by the city and 2) *adaptive capacity* of the households confronted with insufficient services (see Fig. 2 and 3). Citizens' adaptation to deficient services plays an important role in maintaining "tolerable" levels of services, but differences between public and private services are also an indicator of the costs (social, financial, health, etc.), which households carry to cope with insufficient supply. Water supply insufficiencies can impede socio-economic development, and unequal distribution across households can amplify existing economic inequality.

When water supply reserves are depleted during extended droughts, unprepared cities are left with few options, and confront “day zero” scenarios, as was recently the case in Cape Town, South Africa. Melbourne’s response to drought was to increase storage capacity and to invest into large-scale desalination plants (increase of W and I, as P and F were available). Such infrastructure comes at high investment and maintenance costs, and intensifies the sunk-cost effect with resulting lock-in of traditional, centralized urban water supply systems (Marlow et al., 2013). Risk aversion of urban water managers typically drives systems to develop excess resources, if the necessary capitals are available. The sunk-cost effect, legacy of long-lived infrastructure and resulting lock-in of conventional infrastructure bears the potential of a trap, which is characterized by positive feedbacks of increasing investment, growing cost, and increased rigidity (“rigidity trap”). Rigid systems are less flexible in responding to changing environmental conditions (e.g., climate, land use, etc.) and corresponding changes in water availability, changing demands, as well as the emergence of new technologies. Instead, focus should be on diversification and flexible technological solutions, including water recycling and demand management. Measures towards “water-sensitive urban design” followed only after pressure from the community on urban managers increased in Melbourne (Ferguson et al., 2014).

Cities on a more adaptive path develop their water supply systems to meet and manage demands in order to avoid overshooting infrastructure development beyond necessity. Adaptive responses to changing environmental conditions or demand variations maintain a certain level of flexibility, and are able to achieve sufficiency (here: Singapore, Berlin; high water availability in Berlin due to declining demand; see case study description in *SI*). Continuous, adaptive management of services allows adaptation to changing demands and environmental conditions, and maintenance of community adaptive capacity helps coping with unexpected shocks and disturbances.

Low-to-medium capital values indicate systems that are in a transitional state, either being in the process of developing the capitals required to operate and maintain infrastructure systems (e.g., Amman), or that have developed systems with high levels of private and/or self-supply (Chennai). Neglected infrastructure, accelerating dilapidation of urban water systems, and degradation of services can result, if urban growth exceeds the city's ability to maintain existing systems (here: Mexico City).

Chennai's citizens have developed strong adaptive response to highly variable and insufficient water services. Given the ability of the community to access additional, decentralized water resources, Chennai could capitalize on this decentralized system and make services safer and more reliable. This would require a centrally managed and monitored system with decentralized sources, which could have less trade-offs and be more cost-effective than expanding the exploitation of water resources to greater distances, and maintaining a centralized system.

Decision-makers and managers influencing Amman's urban water security are in the process of accessing additional water resources by building desalination plants and large-scale water transfers into the capital (Ray et al., 2012). While this will increase available water resources, the repair and expansion of existing infrastructure is required to avoid degradation and decline. Water tariffs will need to be increased, if the spiral of cost increase and donor-dependence is to be decelerated. While population growth may force urban managers to access additional water resources, improving the robustness of current capitals (W, I, F, P) should also receive increased attention.

Ulaanbaatar's recent population increase requires significant investments into infrastructure to improve its services. International financial donors and technical support organizations, although suggesting demand management as a solution, usually focus on centralized technical solutions in their funding schemes. If adequate financial capital for maintaining such expensive technological systems is lacking, gradual deterioration of infrastructure is likely (e.g., leaks in pipes; inadequate treatment), thus perpetuating dependence on external financial resources. Urban growth, lack of capitals, and degradation of infrastructure and governance institutions will make cities water-insecure. Inability to provide sufficient services has impacts on the socio-economic development of urban communities, and inability to generate sufficient capitals can be considered a poverty trap.

Our results show that, while most cities are able to push *average availability* to cover the majority of average demand, our estimations of water *services* and *security* are often well below acceptable standards.

5 Conclusions

Managing urban water security requires the balance of multiple capitals and management of risks. We propose a simple aggregate measure of the five capitals as a proxy measure, although services result from dynamic exchanges and "conversion" of capitals (e.g., F spent for I, P used to make F more efficient and to negotiate access to W, etc.). Future research could address the issue of capital aggregation based on knowledge of how to "unpack" and model interactions of capitals for the provision of services represented here by CP. Also, systematic research into inequalities beyond city averages is required for a better representation of urban heterogeneity of urban water security.

Risks, such as floods, droughts, earthquakes, economic crises, etc. cause shocks and disturbances to urban water security. While high levels of CP coincide with minimized risks (i.e. reduced vulnerability) (Cai et al., 2017), and robustness allows cities to buffer shocks, future research addressing dynamic system behavior of urban water systems is needed. This includes investigations into the resilience of urban water systems (i.e., their temporal shock-recovery dynamics and potential of tipping points), which consider system complexities and the dynamics created by positive feedback loops. As cities respond to shocks and disturbances, the adaptive capacity marshaled by the capital portfolio is crucial in the adaptation process.

Application of the CPA allows a quantitative and integrative assessment of urban water supply security at the city scale, and provides a tool for comparative analyses across different types of cities. The CPA was developed with the goal of making it applicable to cities of any size and in any location. Normalization occurs at the system scale (to per capita values) and the complementarity of public and private supply are taken into consideration, which are two important prerequisites for this goal. Further testing of the CPA framework to a large number of cities is required to validate the approach.

We suggest that a systematic and holistic assessment of urban water security needs to account for the five capitals. However, data availability constraints may challenge a wide-spread application of the approach: While data for quantifying volumetric water availability (W) is widely accessible, the availability and reliability of city-scale data required for quantifying F, I, P and A exist at varying quality across cities, which results in uncertainties in the quantification of capitals. Monitoring data of the various elements comprised in I are widely available for cities located in developed countries, but are sparser and more difficult to access for most cities in the rest of the world. Community Adaptation (A) is not generally monitored and currently relies on data published on a case study basis. Information about internal processes regarding decision-making and management (P) are mostly lacking.

The case studies presented here are characterized by relative data abundance, as significant prior research has been conducted there. These cities may be regarded as archetypes, and their CPA portfolios may serve as orientation for future assessments of cities, where adequate data is lacking. Nonetheless, since the provision of services relies not only on the availability of W, efforts should focus on improving data availability on the whole capital portfolio, in particular A and P, as the management and maintenance of urban water security depends on these human elements. In addition, while large W is one indicator of urban water supply security, excessive W can also be an indicator of profligate water use and a lack of demand management. This raises the question of the sustainability of current urban water security.

Finally, in the context of the water-energy-food nexus, holistic management of urban security is required, and future research should investigate possibilities for adapting this framework to other critical urban services, such as sanitation, and energy and food supply.

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Supplementary Information for Manuscript

"Quantifying Urban Water Supply Security Under Global Change"

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S.1. Quantification of the Five Capitals

The Capital Portfolio Approach (CPA) presented in this article comprises the quantification of Urban Water Supply Security (UWS) based on the assessment of three dimensions (capital availability, robustness and risk). A hierarchical aggregation process is used: Each capital aggregates several attributes through additive or multiplicative aggregation, or a mix of both. The aggregation method is based on empirical testing of available methods and choice of the one that best fits available data and information. Simple metrics for the quantitative assessment of complex system functions such as urban water supply services are lacking, which requires the aggregation of diverse sets of indicators, as is done for the assessment of the human development index (HDI) or sustainable urban development (Brelsford et al., 2017; Stanton, 2007). A detailed description and implications of the various aggregation methods are discussed in Langhans et al. (Langhans et al., 2014). We defined metrics that represent the set of aspects of UWS (volumetric water availability, access, safety, continuity, reliability, quality and perceived risk), whose logic defines their salience. In the aggregate, however there exists no single, empirically measurable metric of urban water services and security, as defined here. Whether our choice of aggregation is "correct" is a normative question, depending on whether "security" is regarded from a volumetric, technical, or ethical perspective. Based on field research in two of the case studies and a review of the literature on both methods of quantifying urban water security as well as data and information on the case studies, we chose the method that best represents our knowledge of urban water supply security.

S.1.1 Availability

Urban water resources (*W*) are calculated from the annual volume of water accessed for urban uses, including naturally available, captured, reused, desalinated water, etc. ("Urban Water Availability", UWA in [m^3y^{-1}]). 50 m^3 per capita and year [$m^3cap^{-1}y^{-1}$] is used as urban water scarcity threshold. 40 $m^3cap^{-1}y^{-1}$, or 100 lpcd (liters per capita and day) was suggested as a primary consumption requirement (Falkenmark et al., 1989; Savenije, 2000).

Residential water use typically accounts for 60-80% of urban uses (see e.g., (Brears, 2017; BWB, 2016; WB, 2013)), while the remainder is used for commercial, industrial or operational purposes. We therefore add 20% to the primary consumption threshold to reach the urban water scarcity threshold, and consider cities with water availability twice this threshold under "no stress". Urban water resources (W) is the ratio between per capita UWA and the "no stress" threshold (**Table S.1**).

Table S.1: Summary of urban water stress (WS) thresholds, and corresponding W metric.

category	WS threshold ($m^3cap^{-1}y^{-1}$)	W
no stress	>100	>1
scarcity	100-50	1-0.5
water stress	50-25	0.5-0.25
high water stress	<25	<0.25

Infrastructure (I) for urban water supply includes reservoirs, wells, canals, pipelines, pumping stations, desalination and treatment plants that produce and transport water to the city, as well as the storage and distribution network within the urban boundaries. The state of infrastructure is measured by assessing its capacity to deliver water resources (*W*) to all urban customers at adequate quality. Dimensionless *I* is calculated as follows (Eq. S.1)

$$I = h * S_W - q * W_{Drink} \qquad \text{(S.1)},$$

where *h* [-] is the fraction of households connected to the public water supply infrastructure (number of households connected/total number of households); S_W [-] is the fraction of water delivered:

$$S_W = \frac{UWA - W_{leakage}}{D_W} \qquad \text{(S.1a)},$$

where S_W is capped at D_W (i.e., $S_W \leq 1$), $W_{leakage}$=leakage [m^3y^{-1}] and D_W = demand [m^3y^{-1}]. The fraction of *drinking* water over total demand (W_{Drink} [-]) is subtracted from *I* if water is not delivered at drinking water quality (*q=1*, otherwise, *q=0*). Drinking water demand is 7.3 $m^3cap^{-1}y^{-1}$, equals 20 lpcd (standard recommended by the World Health Organization):

$$W_{Drink} = \frac{7.3\ pop}{D_W} \qquad \text{(S.1b)},$$

where *pop* [cap] is the total urban population. When *I* = 1, all available urban water resources are delivered at drinking water quality to all households at demanded volumes.

Financial capital (*F*) is calculated as

$$F = \frac{income}{expenditure} * I \qquad \text{(S.2)}$$

where *income* [$\$y^{-1}$] is the average annual water sector income (averaged over 5 years) and *expenditure* [$\$y^{-1}$] is the average annual water sector budget spent *on operation and maintenance*. *F* is the money available/spent for building, operating and maintaining *I*. *F* is multiplied by *I* to reflect funding needed for the development of new infrastructure (i.e., F is reduced for I<1 to reflect the need for investment). A surplus in the income/expenditure ratio is required to allow for infrastructure investment. When $F = 1$, financial capital covers the costs for operating and maintaining fully functional infrastructure services to all citizens, or for filling the infrastructure gap (income/expenditure >1, when I<1).

Management power (P) is assessed based on 12 metrics in three categories, as shown in **Table S.2**. When P = 1, the city has efficient, flexible, and accountable water institutions with adequate complexity for operating, maintaining, and adapting the urban water system.

Binary scores for each of the metrics indicates 1=present and 0=absent. P is the average score of all 12 metrics. In contrast to the quantification of the other four capitals, we use an aggregate binary score here, because 1) agreed upon quantitative measures of management power for water security, and 2) data to support such measures are lacking. We suggest metrics that have causal relevance for functional water supply services. Their choice is based on critical management criteria identified during key stakeholder interviews conducted for this study (Amman and Ulaanbaatar), as well as governance indicators identified in the literature (Akhmouch and Correia, 2016; Araral and Yu, 2013; Cook and Bakker, 2012; Grey et al., 2013; Gupta et al., 2013; Marlow et al., 2013) that are comparable across cities, and that have proven useful elsewhere (Regulatory complexity metrics are based on Padowski et al. 2016).

Table S.2: Metrics for the assessment of Management Power (P).

Category	Assessment metric	Score
institutional efficiency	clear structure with communication protocols for information sharing	1 / 0
	feedback-loops	1 / 0
	mechanisms for inter-sector coordination	1 / 0
	training & innovations for resilience and sustainability	1 / 0
accountability	mechanisms for participatory decision-making/management	1 / 0
	mechanisms for follow-up of customer complaints	1 / 0
	integrity: Corruption Perception Index > 50	1 / 0
	administrative losses < 10%	1 / 0
regulatory complexity	urban-urban / urban-rural strategies	1 / 0
	transboundary agreements	1 / 0
	mechanisms for groundwater management	1 / 0
	mechanisms for surface water management	1 / 0
		P = Σ(scores)/12

Providing safe, reliable, and affordable water supply to all citizens requires strong and efficient governance. This includes adequate organizational structures and efficient information sharing, feedback loops for the identification of bottlenecks and the possibility for a timely adjustment of processes (Allan et al., 2013). As urban water infrastructure is co-located with roads and traffic, sewers, power lines and communication networks (Mair et al., 2017), coordination among urban infrastructure sectors facilitates maintenance, and increases institutional efficiency by reducing installation costs and damage caused by the construction and repair of infrastructure networks. Complex infrastructure and governance systems facing increasing uncertainty need to overcome lock-in and legacy effects by embracing paradigm shifts in urban water management (Larsen et al., 2016; Marlow et al., 2013; Rauch and Morgenroth, 2013). Institutions and organizations must be flexible and open to innovations, in order to manage rapidly changing demands and conditions of availability.

Accountability of policy-makers and managers is crucial for achieving acceptance for changes and adjustments when needed, and to maintain a willingness to pay for services among the population. While corruption compromises efficiency, perceived corruption degrades institutional accountability. The Corruption Perception Index (Transparency International, 2016) reflects integrity at a country level, which is applied here to the respective cities.

Complex governance and institutions may be necessary to access water from distant places, across borders, or through technologically advanced infrastructure (Grey et al., 2013; Padowski et al., 2016). Scarce resources may be competed for among sectors, cities and countries, requiring institutional agreements for water sharing (Floerke et al., 2018; Gupta et al., 2013).

Community Adaptation (A): Citizens' *adaptation* to insufficient supply contributes to the functioning of water services. Citizens adopt a range of strategies for increasing their water availability and for dealing with insufficient, unsafe, and unreliable services, or the lack of piped water access. These include accessing alternative water services and sources (e.g., delivered by trucks, at water kiosks, or from stores; wells, rivers, harvested rainwater), installing storage capacity in the house, adapting water use behavior, reusing water, treating water to make it safe to drink, and sharing water among neighbors (Rosenberg et al., 2008; Zug and Graefe, 2014). Based on data and information available on the seven case studies, we selected three quantifiable attributes to serve as indicators of community adaptation: A is an aggregate measure of 1) additional water resources accessed by the community (W_{extra}); 2) supply gaps bridged by storing and rationing water use at the household level (g), and 3) the water quality term from Eq. 1, which is added, if water is not delivered at drinking water quality (Eq. S.3):

$$A = \frac{W_{extra}}{D_W} + g * \left(1 - (S_W + \frac{W_{extra}}{D_W}\right) + q * W_{Drink} \qquad \text{(S.3).}$$

The supply gap (g) is a fraction of time, e.g., water delivered on one day per week has a supply gap of 6/7. It can be difficult to quantify W_{extra}, unless household surveys or other prior work was done to quantify additional water resources accessed by households. Upper and lower uncertainty bounds can be calculated by setting $W_{extra}= 0$ (lower bound), and $W_{extra}= 1 – S_W$ (upper bound).

When A = 1, available water services are fully covered by community adaptation, and public services = 0. Thus, when public water supply meets demand, citizens have no need to adapt, and A = 0. Therefore, A does *not* represent the community's *capacity* to adapt, but the *actual adaptation* to insufficient services.

Data for the attributes of A are not routinely monitored and reported for cities in a standardized way. Data used here is drawn from reports and scientific literature as cited in the case study descriptions (see Section S.3 below), as well as utility data (UWA, S_W and meter readings) received for Amman and Ulaanbaatar.

S.1.2 Robustness

Water resource robustness is estimated using, among others, metrics applied for country-scale water scarcity assessments (e.g., (Raskin et al., 1997); for a review see (Liu et al., 2017)). They comprise:

1) The *storage-to-flow ratio* measures the capacity of water infrastructure to cope with fluctuations. It is calculated as the average reservoir storage capacity for urban uses divided by average annual water supply;

2) *Import dependence*: the percentage of urban water resources that flow from external sources (across national or other administrative boundaries), measures the political security of these

resources. Imports depend on developments in neighboring countries/regions, and on the maintenance of transboundary allocation arrangements;

3) *Use-to-resource ratio*: annual withdrawals divided by annual renewable water resources; provides a gauge of the average pressure on resources, and the threat to ecosystems and cities. High allocations to agriculture may be re-allocated to human uses when needed (restricted by inter-seasonal rainfall variability, available infrastructure and water quality (Srinivasan, 2008)). Environmental flow requirements are only slowly being implemented in regulations around the world, but these too are likely to be used as a "buffer" to be exploited in the case of emergency;

4) *Source diversity*: access to multiple sources and source types means that if one of the sources is depleted or polluted, the system can rely on the other sources, with reduced total water availability;

5) *Water quality protection*: Measures with increasing degree of water quality protection are: 1) continuous water quality monitoring, 2) implementation of emissions regulations, 3) control of pollution sources and application of the "polluter pays principle", as well as 4) implementation of the precautionary principle, which avoids potential pollution by prohibiting any uses in the catchment area that could pose a threat to water quality (Borchardt and Ibisch, 2013).

Table S.3 presents the calculation of water resources robustness.

Table S.3: Water resource robustness metric (W_R) with associated stress levels and metric scores.

Metric (score)	no stress (4)	low stress (3)	stress (2)	high stress (1)	score
storage-to-flow	> 0.6	0.6-0.3	0.3-0.2	< 0.2	1-4
import dependence	< 0.15	0.15-0.25	0.25-0.50	> 0.50	1-4
use-to-resource	< 0.1	0.1-0.2	0.2-0.4	> 0.4	1-4
water quality	precautionary principle	source control & polluter-pays	emissions regulations	monitoring	0-4
source diversity	multiple types	two sources & types	one type	one source	1-4
				W_R:	Σ(scores)/20

We used 9 metrics in three categories to estimate **infrastructure robustness**: *I) Operation & Maintenance*: 1) anticipatory maintenance, 2) continuous supply, 3) emergency solutions for power failures, 4) inter-sector coordination, 5) monitoring system for leakage detection; *II) Structural Constraints:* 6) average materials age (<50 years), 7) redundancy in network nodes, 8) existence of decentralized sources, 9) possibility of emergency zone isolation.

Infrastructure degrades from aging of materials and technical parts, and the quality of infrastructure construction, installation, and operation (e.g., pressure control, supply rationing) impact the occurrence of leakages (Christodoulou and Fragiadakis, 2015). Continued and anticipatory maintenance reduces the likelihood of failure (Tscheikner-Gratl et al., 2015). Coordination and information-sharing among infrastructure sectors reduces the risk of failure due to the co-location and interdependence of multiple infrastructure networks (Mair et al., 2017). Water supply systems depend on reliable energy supplies, and risk severe breakdowns if not prepared for emergency situations (Chen et al., 2009). Decentralized sources and the possibility of isolating damaged and contaminated zones within the network can reduce vulnerability.

Financial robustness is assessed by: 1) Income status (available support for unexpected expenditures depends on available funds), 2) the degree of energy autonomy (due to the energy-intensity of the water sector), and 3) dependence on international donors for infrastructure investment. Unexpected population and energy price changes, infrastructure failure, or changes in the availability and quality of water resources challenge financial water sector planning. In emergency cases, government support should cover unexpected financial demands. *F* usually has two main sources: 1) water fees and tariffs charged to the customers according to water consumption and services provided, 2) governmental subsidies or donor funding. Different operating models rely on the two sources to varying degrees, and cover a spectrum from autonomous to heavily dependent systems. Water systems with autonomous funding (full cost recovery) are financially less vulnerable than donor- and subsidy-dependent systems.

Management power is parameterized by *internal preparedness*, including 1) the existence of emergency operations planning, and 2) the capacity to improvise, innovate, and expand operations (Rourke, 2007), as well as *external factors*: 1) the existence of national planning or human resource aid mechanisms that support the recovery from disasters; and 2) city ranking, i.e. importance of the concerned city on national (capital cities versus secondary cities), and geopolitical scales.

Community resilience: Options for adaptation and community vulnerability depend on household-scale characteristics: 1) financial capacity (disposable income), measured by the community's *median* income (using the World Bank threshold for middle-income countries); 2) access to alternative water services (i.e. private market); 3) direct access to water sources, such as wells or the proximity of rivers; 4) capacity to store water within the household (capacity of 7 days of drinking water demand); 5) whether people treat water before they drink it or drink bottled water, only; 6) access to information for improved response to emergency situations; 7) active community structures as a support network (e.g., for water lending).

Each of the robustness metrics is calculated as the summed scores average of the presented sub-metrics (as shown in Table S.3; otherwise 1=present, 0=absent). The lower a city's robustness, the larger the impact of shocks and disturbances on urban water security.

S.1.3 Risk

Table S.4: Risk assessment scoring system.

Hazard category	Hazard / impact type	Susceptible capital	Risk type	City risk score
Geological and geographic hazards	earthquakes, tsunamis, volcanic eruptions, landslides	I A	acute	(1/0)
	land subsidence	I	chronic	(1/0)
Socio-economic and geo-political threats	socio-economic/political changes/ unforeseen high immigration rates	W I F P A	chronic	(1/0)
	immediate threat of terrorism/war	W I F P A	acute	(1/0)
	competition for resources	W P	chronic	(1/0)
	illegal tapping into water pipes	I	chronic	(1/0)
	immediate threat of economic crises	F P A	acute	(1/0)
Contamination hazard	industrial spills (upstream industry)	W I A	acute	(1/0)
	health impacts/epidemic incidents through degraded infrastructure (e.g., in combination with floods)/ groundwater degradation from intensive farming and lack of sanitary infrastructure	W I A	chronic	(1/0)
Climate & weather-related hazards	storms and wildfires (potential of damaging infrastructure)	I	acute	(1/0)
	floods/drought	W	acute	(1/0)
	extreme temperatures (freezing & bursting of pipes)	I	chronic	(1/0)

S.1.4 Aggregation of the Capitals

Water supply services include 1) total water volumes supplied, 2) the connection rate of households to public supply, 3) the quality of water supplied (drinking/non-drinking water quality), and 4) management response to failure, as well as other aspects of services, such as the continuity of supply, demand management, etc. These services are achieved through the interaction and balance of the four capitals contributing to public water services (W, I, F, P). Investigating the actual interaction of the capitals is beyond the scope of this study, and we propose here a simple average aggregate (harmonic mean) as a proxy measure. We use the harmonic mean, assuming that significant lack of one of the capitals leads to a reduction of service overall, compared to a more balanced distribution of capitals:

$$CP_{public} = \frac{4}{\sum \frac{1}{C_i}} \qquad \text{(S.5)}$$

where $C_i = [W, I, P, F]$. Equivalently, the Capital Portfolio including the adaptive response of the community is defined as:

$$CP_{total} = CP_{public} + A \qquad \text{(S.6)}$$

where A is assumed to replace public services, as people are forced to rely on self-services when public services are lacking.

Testing of alternative aggregation methods showed that the arithmetic mean systematically overestimates services, while multiplicative aggregation tends to underestimate services for cities with service deficit.

The Robustness Portfolio is calculated as the arithmetic mean of capital robustness:

$$RP_{public} = \frac{\sum R_{i(public)}}{4} \qquad \text{(S.7)}$$

where $R_{i(public)} = [W_R, I_R, P_R, F_R]$. The arithmetic mean appears justified here, because "balance" is less important for robustness, and substitutability is more realistic in the case of robustness than in the case of availability. For example, if infrastructure fails due to a lack of robustness, I is reduced, but can be recovered by P_R and F_R, even though I_R is low. In addition, robustness of community adaptive capacity significantly increases system robustness, however it is not independent of overall system robustness. For example, in case of a drought, all water resources will be impacted, including alternative water sources accesses by the community. Therefore, total robustness, including community robustness (A_R) is:

$$RP_{total} = \frac{\sum R_{i(total)}}{4} \qquad \text{(S.8)}$$

S.2. Results: The CPA for Water Security

Data of the CPA are provided in Table S.5.

Table S.5: Capital availability values, robustness, and risks, with results for water supply (S_W) and services (CP) for seven case study cities. Full services at CP = 1; for CP > 1, cities have buffering capacity to maintain services for increased D_W/UWA ratio.

Capitals	Amman	Berlin	Chennai	Melbourne	Mexico City	Singapore	Ulaanbaatar
W	0.44	1.12	0.50	3.21	1.23	0.73	0.51
I	0.67	0.97	0.23	0.98	0.39	1.00	0.32
F	0.72	1.08	0.18	1.13	0.31	1.15	0.27
P	0.33	1.00	0.25	1.00	0.17	1.00	0.17
A	0.25	0.01	0.53	0.01	0.21	0.01	0.18
CP_{public}	0.51	1.04	0.25	1.24	0.38	0.94	0.27
CP_{total}	0.76	1.04	0.78	1.24	0.59	>0.94	0.47
S_W	0.65	1.00	0.55	1.00	0.88	1.00	0.83
S_{Wtotal}	0.73	1.00	0.90	1.00	1.00	1.00	0.88
UWA/D_W	0.87	2.31	1.25	5.46	1.59	1.34	0.90
W_{extra}/D_W	0.12	0.01	0.35	0.01	0.06	0.01	0.18
Robustness							
W_R	0.60	0.80	0.65	1.00	0.60	0.70	0.55
I_R	0.44	0.89	0.22	1.00	0.44	1.00	0.33
F_R	0.33	0.67	0.33	1.00	0.33	0.67	0.67
P_R	0.75	1.00	0.25	0.75	0.50	1.00	0.25
A_R	0.71	0.71	0.71	0.57	0.71	0.57	0.29
RP_{public}	0.48	0.82	0.31	0.92	0.45	0.81	0.37
Risk	0.43	0.06	0.62	0.06	0.62	0.14	0.57

S.3. Urban Case Studies

Chennai: Water supply to the city (5.5 million inhabitants, 9.5 in the metropolitan area) is covered by five surface water reservoirs, as well as 6500 wells extracting local groundwater.[1] In a normal year, this water is assumed to cover 65% of water demand (50 $m^3cap^{-1}y^{-1}$, black line in top left panel Fig. 1), while the remainder is covered by the private market and self-supply from wells and other sources (Venkatachalam, 2015) (total UWA from all sources is 30-104 $m^3cap^{-1}y^{-1}$).

During a severe drought in 2003-2004 these water resources dried up, forcing the water utility to turn off piped water supply for an entire year. To increase water availability and meet rising demands, as well as decrease variability of supply in response to drought (lower bound of shaded area in Fig. 1), the city started investing in desalination plants, and promoting urban rainwater harvesting (enhanced urban groundwater recharge).[2] Given the large variability in water availability, infrastructure comprises too little storage to reliably provide water services. Although 95% of Chennai's population have access to some sort of public water supply, such as public hand pumps or taps, piped household connections, or water supplied by utility-run tanker trucks, water supply is intermittent and available only for a few hours each day (Srinivasan et al., 2010). Piped household connections are available to 35% of the urban population (48% of non-slum dwellers) (Chandramouli, 2003), and degradation of water supply infrastructure results in water leakage losses of around 28% (Srinivasan, 2008), putting piped water quality at risk from contamination. The wide range of types of water access with variability across space and time, and uncertainty of water quality produce a wide range between upper and lower bound for the state of infrastructure (shaded area of I in Fig. 1).

Water supply in Chennai is heavily subsidized (30% of operation and maintenance (O&M) expenditures), and revenues cover merely 50% of expenditures, so that capital for infrastructure investment is lacking. Upper and lower bounds of F (shaded area) are minimum and maximum income over spending ratios in Chennai for the years 2007-2013.[1]

During the 2003-2004 drought, the local water utility switched its services from reservoir management and piped water supply to hiring water trucks and extracting water from peri-urban areas. With the support of the local government it silenced protests from peri-urban farmers, who had to quit farming due to the urban-induced water scarcity in their lands. Further conflicts in water access have arisen from the inter-state Telugu-Ganga water transfer scheme (Gopakumar, 2009). Little information is available about the internal functioning of the water utility, which results in a wide uncertainty range for management power (P) (shaded area of P in top left panel of Fig. 1).

Chennai's citizens access water through public water delivered by the piped network or by tanker trucks to public taps or to their houses, using public hand pumps, by drilling wells into the shallow groundwater, or from private water vendors. Most households have adopted mixed strategies to cope with deficient services, as public supplies vary in delivery frequencies and volumes, and the various sources provide different water qualities (local groundwater is brackish in many places). Adaptation options depend on the income levels of households and types of housing (28% of Chennai's population officially lives in slums). The government provides water at public taps and hand pumps at no cost to Chennai's citizens, while households with individual piped connections pay a small fee. However, according to a household survey conducted in one of Chennai's 250 administrative wards, citizens have to pay 'bribes to rent-seekers' on a regular basis for attaining water from these public sources. Apparently, these 'rent-seekers' also maintain the public taps and hand-pumps (Krishnamurthy and Desouza, 2015).

Adaptation of Chennai's citizens is highly variable (shaded area of A in Fig. 1), reflecting the variability in infrastructure services. During the 2003-2004 drought, less than a third of water needs

1 http://www.chennaimetrowater.tn.nic.in

2 http://www.waterandmegacities.org/water-supply-situation-in-chennai/

were covered by utility sources, while the majority came from private wells, which reached a total number of 420,000 (more than two-thirds of households) (Srinivasan et al., 2010).

Ulaanbaatar: Water is supplied to the city from riverbank filtrate, and several thousand private groundwater wells. Increasing withdrawals to meet the demand of Ulaanbaatar's growing population (1.4 million in 2015) results in average urban water availability between 42-69 $m^3cap^{-1}y^{-1}$ (2005-2012 data) from public supply, and 46-73 $m^3cap^{-1}y^{-1}$ from all sources. Average annual discharge of the Tuul River, the city's main water source, halved in the period 2000-2010 compared to 1972-1991 (JICA, 2013), and the river has been reported to run dry during late spring in recent years. Apartment areas (41% of population) are centrally supplied with water, heat, and electricity, while "Ger areas" (59% of population), where the population lives in traditional Mongolian felt tents ("Gers"), or more solid individual housings, lack basic infrastructure services, such as paved roads, piped water supply and sanitation (Myagmarsuren et al., 2015). Water consumption from public sources was 167 lpcd in apartment areas, and 8 lpcd in Ger areas in 2015 (Myagmarsuren et al., 2015).

In spite of Mongolia's recent economic boom, 27% of Ulaanbaatar's population still lived below the national poverty line in 2011 (ADB, 2014), and since then the economy has gone into a steep decline with unemployment on the rise. Public water-related expenditures generally surmount revenues, and although the introduction of water meters and water price increases have improved the water utility's financial situation, investment capital remains lacking (data and projections for income and expenditures are for 2008-2015, (ADB, 2013)). Water supply management in Ulaanbaatar is complex, with hierarchical structures characterizing decision-making, management, and implementation. In spite of attempts to decentralize power, and the implementation of laws regulating the water sector, the overwhelming dynamics of urban growth and demand changes have left many tasks unaddressed. High transaction costs, and lack of transparency and funding impede urgently needed actions to improve water sustainability, and dependencies on international donors reduce the efficiency for smart city planning (Unger, 2012).

Community adaptation in Ulaanbaatar lies on the shoulders of the underserved Ger dwellers, and adaptive capacity in these areas is limited. Ger dwellers walk to fetch water from utility-run water kiosks every day, faced with temperatures as low as -40˚C in winter, and 40˚C in summer. Water supply intermittence can occur during winter (October-April) due to the freezing of pipes. Lack of water infrastructure and sanitation has resulted in the installation of open, unlined pit latrines, which risk contaminating the unprotected and shallow private groundwater wells (64% unprotected wells are contaminated with bacteria), as well as public supplies, which are distributed without prior treatment. Additional water access for Ger dwellers is through the use of public bath houses, or sharing facilities with relatives, who live in apartment complexes (Sigel, 2012).

Amman: Water supply to the city (4.1 million inhabitants) comes from three main sources: 1) the Disi Aquifer located at the border to Saudi Arabia (44%); 2) multiple rivers and surface water dams across the country (44%); as well as 3) springs and wells within the urban limits (12%), resulting in water availability for Amman of 182 million cubic meters per year (MCMy), while demand lies at 210 MCMy (Miyahuna, 2014). Most of these sources originate from transboundary water bodies, and around 30% are imported. Per capita urban water availability is 44.4 $m^3cap^{-1}y^{-1}$, and water delivered from farm wells by private water re-sellers increase this amount to 49.3 $m^3cap^{-1}y^{-1}$ [*Klassert, pers. communication*]. Groundwater sources in Jordan are mostly non-renewable, and several wells have had to be shut down in recent years due to deteriorating water quality and salinization from over-exploitation, making groundwater a viable source only for a few more decades.

98% of Amman's households are connected to the piped water network, and receive water on 2.5 days on average; 80% of households are connected to the sanitary sewer system (Miyahuna, 2014). Water rationing increases infrastructure degradation, and leakage rates are around 23%. Long-distance water transfers of up to 350 km, altitude differences of over 1000 m from source to city, dropping groundwater levels, increasing salinity, and the need for mixing and treatment of raw water of low quality, as well as the need for frequent repairs, and rapid urban growth make water supply financially expensive. While accounting has improved, the sector relies heavily on investment capital from donor grants and loans. Low water tariffs do not cover operation and maintenance costs, making government subsidies necessary on a continuous basis. Jordan almost exclusively relies on energy imports (97%), and electricity prices have sharply increased over the past years (316% since 2010); water sector subsidies accounted for 20% of government deficit (OECD, 2014). The recently commissioned Red-Sea Dead-Sea Conveyance project is to more than double current water availability by 2040, with estimated investment costs at US$ 10.3 billion (Coyne et Bellier et al., 2012).

Water sector management in Amman is characterized by hierarchical structures, overlapping roles and responsibilities, a lack of stakeholder and public participation, and in-transparency of decision-making (Hagan, 2008; OECD, 2014). Public sector employment has low incentives, leading to a high fluctuation of staff, and the lack of management capacities and project development skills.

Amman's citizens have adapted to intermittent and scarce water supply by installing storage tanks, and by resorting to water delivered by private tanker trucks. Variability of household incomes and storage capacities lead to inequality in household water availability (Potter and Darmame, 2010), which is threatened of being exacerbated by increasing demand from population growth, and unsustainable management practices.

Greater **Mexico City**, a conglomerate of over 23 million people (8.5 million in the Federal District of Mexico City), is located in the closed basin of the Mexico Valley. Local natural water availability is 63.3 $m^3cap^{-1}y^{-1}$ (Lankao and Parsons, 2010), which is increased to 123 m^3 by water imports and over-extraction from local surface and groundwater sources (adding water from private wells results in 64-143 $m^3cap^{-1}y^{-1}$). Local sources make up two-thirds of the urban water supply, while the remainder is imported from a distance of over 150 km and raised by 1000 m to reach the urban area (CONAGUA, 2016). The same amount of water imported is lost through leaking pipes.[3] Officially, around 80% of households in the Greater Mexico City area are connected to the piped water supply system, of which around half receive water continuously. The rest of the population has access to piped water outside their houses, or from water supplied by tanker trucks or donkeys.

Sanitary infrastructure is lacking in many parts of the city, and only 10% of wastewater is treated[4] (Tortajada and Castelan, 2003). 60% of construction in the city is informal (Burdett and Sudjic, 2010), making sustainable urban planning and management near impossible. Water scarcity and urban flooding, such as occurred in 2009, demonstrate the city's vulnerability to variability in water availability.[5] Water quality is a considerable concern, making Mexico City one of the world's leading bottled water consumers globally. In poor neighborhoods the prevalence of acute diarrheal diseases can reach 15% (Lankao and Parsons, 2010). Severe land subsidence caused by over-extraction of groundwater and the collapse of subterranean lake sediments causes damage to water pipes, as well as accelerating the need for pumping storm- and wastewater away from the urban basin, in order to avoid flooding. Rainwater can no longer infiltrate the formerly highly productive aquifers due to surface sealing, diminishing groundwater resources. Earthquakes irregularly strike the area, causing damage to infrastructure, and disconnecting additional citizens from the piped

[3] https://www.nytimes.com/interactive/2017/02/17/world/americas/mexico-city-sinking.html
[4] https://www.theguardian.com/cities/2015/nov/12/mexico-city-water-crisis-source-sewer
[5] http://www.nytimes.com/2009/09/13/world/americas/13drought.html

water supply (the September 2017 earthquake of magnitude 8.1 cut piped water supply to 4 million citizens in the valley).

Inter-basin transfers, altitude differences and gradient losses due to land subsidence, make the city's water supply system very costly. The municipalities and water utilities responsible for water distribution, metering, and billing within the Greater Mexico City area struggle to run their water systems efficiently, due to understaffing, financial insufficiencies, and dilapidation of the pipe network. Tariff collection rates are as low as 24%, leading to a highly deficient water sector budget.[6] Unequal public water supply reaches more than 300 lpcd in wealthier districts, and 20-80 lpcd in poorer neighborhoods. Customers in poor neighborhoods wait days to weeks for ordered trucked water supplies; bribing and violence among customers, and between customers and tanker truck drivers are not uncommon. Households spend up to 20% of their income on water, and some are forced to leave the city due to the unaffordability of city life. Citizens have protested against the privatization of water supply[4], and outside the city, water imports put water managers into conflict with local populations, who are trying to fend off the increasing encroachment on their land, lakes, and rivers.[6]

In **Singapore, Melbourne**, and **Berlin**, urban water managers are able to provide water to all citizens at drinking water quality 24/7. Revenues cover O&M costs, and an income surplus of approximately 10% annually, as well as government support provides reserve funds and financial capital for infrastructure expansion and technological advancements. Water supply and drainage are combined in these cities' utilities, and energy production (from hydro-power and/or wastewater treatment plants) is part of their business portfolio. Residents are not required to adapt to deficient water supply services (values for adaptation = 0, right-hand panels in Fig. 1), and relatively high income and social stability result in low vulnerability of citizens' adaptive capacity. A certain level of vulnerability to potential water contamination events remains, because these citizens rely on the provision of drinking water quality, and do not treat water prior to drinking. In spite of the apparent model character of their supply systems, each city faces specific challenges, which require careful attention by the cities' water managers.

Singapore: Following Singapore's independence in 1965, Singapore began its efforts towards the island's water sustainability. Local, natural renewable resources result in average water availability of 74 $m^3cap^{-1}y^{-1}$. "Four taps" provide water to the island, including local catchments (40%), reclaimed "NEWater" (20%), desalinated water (10%), and water imported from the Johor catchment in Malaysia (30%); 45% are supplied for domestic urban uses, and water consumption lies at 150 lpcd (Public Utilities Board (PUB), 2017). Desalination and NEWater production had to balance water lacking due to a rare dry spell in 2014 (Ziegler et al., 2014). Occasional political sparring with neighboring Malaysia motivate Singapore to become more water independent (Lee, 2005). The operation of technologically advanced water production comes at high energy demand and financial costs, which are subsidized by the government in the order of 20%. The country is working towards a higher degree of energy independence through the implementation of renewable energy schemes, which is limited by the small size of the island.

Singapore's water sector is a global hub of international water technology development and implementation, integrated water resources management, and green infrastructure, which offers access to green spaces that serve as water retention and purification areas. The public provider operates transparently and efficiently, coordinates with various other infrastructure sectors to carefully manage the sophisticated water infrastructure, and involves the public into its efforts towards sustainable water management.

Melbourne: Ten storage reservoirs located in Melbourne's surrounding catchments provide an average of 320 $m^3cap^{-1}y^{-1}$ to 4 million citizens. While on average water is abundant, during the

[6] https://en.wikipedia.org/wiki/Water_management_in_Greater_Mexico_City

1997-2010 drought storage levels fell to a low of around 30%, bringing the city close to its limits of reliable water supply (MelbourneWater, 2017). The drought caused major changes to the city's water governance, and included the incremental introduction of water demand management measures, wastewater recycling for non-potable uses, and the construction of a desalination plant for additional drinking water supply, as well as the enhanced protection of source areas, and treatment of storm water to protect urban waterways (Ferguson et al., 2013).

Berlin: Berlin's 3.6 million inhabitants are supplied by groundwater (60%), riverbank filtrate of the Spree and Havel Rivers (29%), and water from enhanced aquifer recharge (11%) (BWB, 2016). Total water availability lies at 400 MCMy, while demand lies at half that. Demand has decreased by around 30% since 1991, as a result of the decline of industrial production in the area after the German reunification, as well as reduced domestic water demand (current: 110 lpcd) (Moeller and Burgschweiger, 2008). Only 9 out of 13 water purification plants are currently in operation. Water quality is carefully monitored and controlled, as natural groundwater salinity and local permanent, as well as temporal groundwater contamination are present in Berlin's water sources. The riverbank filtrate is subject to a fragile balance of managed water landscapes: For several decades and until the late 1990's two-thirds of runoff in the Spree River resulted from groundwater pumped from lignite mines, and, after the closure of the mines, a new hydrological equilibrium is still forming. Due to the flat terrain, the river naturally flows at low velocities, and variations in water availability can cause temporally low water conditions, during which the river almost exclusively carries treated wastewater and can cause the river to flow backwards (Zens, 2003). Sulfate contamination washed out from the former mining landscapes, and as a result of agricultural practices, are an increasing concern for drinking water quality, the occurrence of algal blooms, and the survival of river organisms, as well as contributing to infrastructure degradation (IGB, 2016). The local water provider is taking measures to prepare for the decreasing source water quality. The dashed line of W in the lower right-hand panel of Fig. 1 reflects Berlin's water quality vulnerability.

Berlin's financial indebtment during the 1990's led to the partial privatization of the water utility in 1999 with the involvement of multinational corporations. A result was the lay-off of 2000 employees and replacement by temporary workers, as well as water price increases of 20% within a couple of years (Passadakis, 2006). Public opposition and law enforcement measures followed, and the utility was returned into full public ownership of the State of Berlin in 2014/2015. Major efforts have since turned the utility into a responsible and transparent public company, which seeks to benefit society by safe and reliable water provision, ecosystem protection, as well as through social integration and gender equality (BWB, 2016).

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