DYNAMICS OF COUPLED NATURAL-HUMAN-ENGINEERED SYSTEMS: AN URBAN WATER PERSPECTIVE ON THE SUSTAINABLE MANAGEMENT OF SECURITY AND RESILIENCE

by

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shrouded entropy

play of time and elements

universe dancing

[E.A. Rosenfeldt]

Giants' Shoulders

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Abstract

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The security, resilience and sustainability of water supply in urban areas are of major concern in cities around the world. Their dynamics and long-term trajectories result from external change processes, as well as adaptive and maladaptive management practices aiming to secure urban livelihoods. This dissertation examines the dynamics of urban water systems from a social-ecological-technical systems perspective, in which infrastructure and institutions mediate the human-water-ecosystem relationship.

The three concepts of security, resilience and sustainability are often used interchangeably, making the achievement of goals addressing such challenges somewhat elusive. This becomes evident in the international policy arena, with the UN Sustainable Development Goals being the most prominent example, in which aspirations for achieving the different goals for different sectors lead to conflicting objectives. Similarly, the scientific literature remains inconclusive on characterizations and quantifiable metrics. These and other urban water challenges facing the global urban community are discussed, and research questions and objectives are introduced in Section 1.

In Section 2, I suggest distinct definitions of urban water security, resilience and sustainability: Security refers to the state of system functioning regarding water services; resilience refers to ability to absorb shocks, to adapt and transform, and therefore describes the dynamic, short- to medium-term system behavior in response to shocks and disturbances; sustainability aims to balance the needs in terms of ecology and society (humans and the economic systems they build) of today without compromising the ability to meet the needs of future generations. Therefore, sustainability refers to current and long-term impacts on nature and society of maintaining system functions, and therefore affects system trajectories. I suggest that sustainability should include not only local effects, but consider impacts across scales and sectors. I propose methods for the

quantification of urban water security, resilience and sustainability, an approach for modeling dynamic water system behavior, as well as an integrated framework combining the three dimensions for a holistic assessment of urban water supply systems. The framework integrates natural, human and engineered system components ("Capital Portfolio Approach") and is applied to a range of case study cities selected from a broad range of hydro-climatic and socio-economic regions on four continents. Data on urban water infrastructure and services were collected from utilities in two cities (Amman, Jordan; Ulaanbaatar, Mongolia), key stakeholder interviews and a household survey conducted in Amman. Publicly available, empirical utility data and globally accessible datasets were used to support these and additional case studies.

The data show that community adaptation significantly contributes to urban water security and resilience, but the ability to adapt is highly heterogeneous across and within cities, leading to large inequality of water security. In cities with high levels of water security and resilience, adaptive capacity remains latent (inactive), while water-insecure cities rely on community adaptation for the self-provision of services. The framework is applied for assessing individual urban water systems, as well as for cross-city comparison for different types of cities. Results show that cities fall along a continuous gradient, ranging from water insecure and non-resilient cities with inadequate service provision prone to failure in response to extant shock regimes, to water secure and resilient systems with high levels of services and immediate recovery after shocks. Although limited by diverse constraints, the analyses show that urban water security and resilience tend to co-evolve, whereas sustainability, which considers local and global sustainable management, shows highly variable results across cities. I propose that the management of urban water systems should maintain a balance of security, resilience and sustainability.

The focus in Section 3 is on intra-city patterns and mechanisms, which contribute to urban water security, resilience and sustainability. In spite of engineering design and planning, and against common expectations, intra-city patterns emerge from self-organizing processes similar to those found in nature. These are related to growth processes following the principle of preferential attachment and functional efficiency considerations, which lead to Pareto power-law probability distributions characteristic of scale-free-like structures. Results presented here show that such structures are also present in urban water distribution and sanitary sewer networks, and how deviation from such specific patterns can result in vulnerability towards cascading failures. In addition, unbounded growth, unmanaged demand and unregulated water markets can lead to large inequality, which increases failure vulnerability.

The introduction of infrastructure and institutions for providing urban water services intercedes and mediates the human-water relationship. Complexity of infrastructural and institutional setups, growth patterns, management strategies and practices result in different levels of disconnects between citizens and the ecosystems providing freshwater resources. “Invisibility” of services to citizens results from maximized water system performance. It can lead to a lack of awareness about the effort and underlying infrastructure and institutions that operate for delivering services. Data for the seven cities illustrate different portfolios of complexity, invisibility and disconnection. Empirical data gathered in a household survey and key stakeholder interviews in Amman reveals that a misalignment of stakeholder perceptions resulting from the lack of information flow between citizens and urban managers can be misguiding and can constrain the decision-making space. Unsustainable practices are fostered by invisibility and disconnection and exacerbate the threats to urban water security and resilience. Such challenges are investigated in the context of urban water system traps: the poverty and the rigidity trap, and the mechanisms leading to and characterizing these traps are explained. Results indicate that urban water poverty is associated with local unsustainability, while rigidity traps combined with urban demand growth gravitate towards global unsustainability.

Returning to the city-level in Section 4, I investigate urban water system evolution. The question how the trajectories of urban water security, resilience and sustainability can be managed is examined using insights from hydrological and social-ecological systems research. I propose an “Urban Budyko Landscape”, which compares urban water supply systems to hydrological catchments and highlights the different roles of supply- and demand-management of water and water-related urban services. A global assessment of 38 cities around the world puts the seven case studies in perspective, emphasizing the relevance of the proposed framework and the representative, archetypal character of the selected case studies.

Furthermore, I examine how managing for the different dimensions of the CPA (capital availability, robustness, risk and sustainable management) determines the trajectories of urban water systems. This is done by integrating the CPA with the components of social-ecological system resilience, which explain how control of the different components determines the movement of systems through states of security and resilience in a stability landscape. Finally, potential feedbacks resulting from the global environment are investigated with respect to the role that globally sustainable local and regional water management can play in determining the trajectories of urban water systems. These assessments demonstrate how the impact of supply-oriented strategies reach beyond local, regional and into global boundaries for meeting a growing urban demand, and come at the cost of global sustainability and communities elsewhere.

Despite stark differences between individual cities and large heterogeneities within cities, convergent trends and patterns emerge across systems and are revealed through application of the proposed concepts and frameworks. The implications of these findings are discussed in Section 5, and are summarized here as follows:

1) The management of urban water systems needs to move beyond the security and resilience paradigms, which focus on current system functioning and short-term behavior. Sustaining a growing global, urban population will require addressing the long-term, cross-scale and inter-sector impacts of achieving and maintaining urban water security and resilience.

2) Emergent spatial patterns are driven by optimization for the objective functions. Avoiding traps, cascading failure, extreme inequality and maintaining global urban livability requires a balance of supply- and demand-management, consideration of system complexity, size and reach (i.e., footprint), as well as internal structures and management strategies (connectedness and modularity).

3) Urban water security and resilience are threatened by long-term decline, which necessitates the transformation to urban sustainability. The key to sustainability lies in experimentation, modularization and the incorporation of interdependencies across scales, systems and sectors.

Four research hypotheses and several propositions guide the investigations and conceptualizations of Sections 2, 3 and 4. The thesis as a whole presents, in broad strokes, a synthesis of my understanding of urban water security, resilience and sustainability using a coupled natural-human-engineered systems perspective. Some of the hypotheses have been elaborated and supported with quantitative models and empirical evidence, which have been published in or submitted to peer-reviewed journals. The manuscripts that have resulted from this so far are in the appendix. Other propositions are put forward as a basis for further research.

The first manuscript (*Appendix 1)* presents the method for quantifying urban water security (Capital Portfolio Approach, CPA); the second (*Appendix 2*) is on the translation of urban water system metrics into model parameters with dynamic system modeling of urban water resilience. The third manuscript (*Appendix 3*) presents emergent, fractal-like patterns of urban water supply and sanitary sewer networks.

1. Dynamics of Urbanization and Global Change

Urban areas are drivers of global and climate change, centers of innovation, and home to the majority of the global population faced with the impacts of global and climate change (IPCC, 2018; Lobo et al., 2013; UN-Habitat, 2016b). Urbanization and urban lifestyle generate large environmental footprints (Grimm et al., 2008), and cause feedbacks with negative impacts on the security, resilience, and sustainability of humanity (Borucke et al., 2013; Meadows et al., 1972; Newell & Cousins, 2015; Rockström et al., 2009). Although less than 3% of the Earth's surface is considered urbanized area (UN-Habitat, 2016b), we regularly produce an ecological footprint in excess of 100% of the Earth’s renewable resources each year in support of cities and other human systems (Wackernagel et al., 2002). The recent decades abound with evidence of the dynamics caused by human-induced global change, which includes climate change (IPCC, 2014), land use change (Václavík et al., 2013), environmental pollution (UNEP, 2016), socio-economic polarization (Behrens & Robert-Nicoud, 2014), and disasters resulting from the coupling between natural, human, and engineered systems (coupled natural-human-engineered, CNHE; or, used equivalently here: social-ecological-technical systems, SETS). Assessments of ancient urban societies indicate that the dynamics of hydro-social CNHE systems have contributed to the collapse of cities and entire societies, such as the Mayas, the Hohokam, Angkor Wat, and the Harappa (Anderies, 2006; Kuil et al., 2016; Sivapalan & Blöschl, 2015). The disappearance of the Aral Sea and the entire economy that was based on this major water ecosystem is a result of unsustainable irrigation practices (Edelstein et al., 2012). It is the adaptive and maladaptive management choices that determine the evolution of urban water systems specifically, and human-water-ecosystem relationships more generally, and can increase societal vulnerability to climate and global change even today (Barnett & O’Neill, 2010; Juhola et al., 2016; Marlow et al., 2013).

More recent examples of water-related CNHE system disasters are the urban and agricultural water scarcity pressures and devastating wildfires in the Western United States, which have resulted from a combination of arid conditions, drought and rising water demand over the past decade (Cai et al., 2017; Fuller & Turkewitz, 2018; Shannon, 2018); Cape Town facing "Day Zero" following a drought and limited water storage capacity (Welch, 2018); the loss of livelihoods of millions of people in one of the most densely populated areas, Bangladesh's Ganges-

Brahmaputra River Delta, resulting from the armoring of the delta by coastal embankments and ensuing negative feedbacks (Ishtiaque et al., 2017; Rogers et al., 2017), as well as water infrastructure systems challenged to keep up with surging demands due to refugee crises in the Middle East (Vidal, 2016).

Rebound effects that result from the partial implementation of water systems cause human and ecosystem health problems related to water quality impairments. A typical example is the introduction of infrastructure and management systems for securing water supply, and failure or incomplete implementation of adequate sanitation, drainage and wastewater treatment plants (Ashraf et al., 2016; Brown et al., 2009; UNEP, 2016). Inadequate protection of ecosystems that are the producers of fresh water resources, has led to impairments of urban water quantity and quality in developed and developing countries with impacts on human health and livelihoods: São Paulo's lurking water crisis is the consequence of continued deforestation in the Amazon (Nikolau, 2015), and citizens in several US cities, including Pittsburgh (Pennsylvania), have been facing health problems due to groundwater contamination caused by gas fracturing (Lurie, 2016). Moreover, urbanization and other land use changes, e.g. from forest to agriculture, and the wide-spread implementation of drainage systems (e.g., river channeling and tile drains in agriculture) to reduce the risk of flooding, and increase the area of arable land have led to higher variability of stormwater discharge and risk of downstream urban flooding (Bronstert et al., 2002; Douglas et al., 2008; Eakin et al., 2016; Schulze, 2000). Persistent and rising inequality in developed nations adversely affects the urban poor, including health threats related to lead poisoning in East Chicago (Indiana) and Flint (Michigan) (Sampson, 2017). Cities located along coastlines and in the world’s coastal river deltas are confronted with the risks of sea level rise, which threaten urban infrastructure, coastal freshwater resources, and urban livelihoods (Xian et al., 2018). These include many cities in the world’s leading and developing economies, including New York City, Shanghai, Singapore, Bangkok, and many others.

Growing public awareness of these and other problems has caused decision-makers to launch a range of strategic initiatives and action plans addressing urban water security, resilience and sustainability. These include the Millennium Development Goals declared at the UN-Summit in Johannesburg in 2002 (United Nations, 2015b) followed by the Sustainable Development Goals (UN, 2018), Rockefeller's 100 Resilient Cities (ROCKEFELLER FOUNDATION, 2016), ICLEI's Resilient Cities program (ICLEI, 2016), C40 Cities (C40 Cities, 2016), and the Urban Resilience

Hub hosted at UN-Habitat (UN-Habitat, 2017), to name but a few. Whether part of a global strategic initiative, or as individual efforts towards adaptation to climate change, cities worldwide are working towards improving their water systems. Their efforts reflect the wide range and local characteristics of urban water challenges, as well as adaptive capacities and priority setting in various contexts. The achievement of ambitious goals proves to have its constraints for a range of reasons (United Nations, 2015b), including the lack of quantifiable metrics and a clear definition of targets (Hoekstra et al., 2018). Competing goals and interests (Floerke et al., 2018; Kelly et al., 2015; Siciliano & Urban, 2017; Swyngedouw, 2009) and unintended consequences of well-intended projects (Brown et al., 2009; UNEP, 2016), as well as limited access to financial and other types of capital additionally constrain measurable advancements (Béné et al., 2014; Eakin et al., 2016; Fothergill & Peek, 2004; Sullivan, 2002).

The following sections are organized as follows: The remainder of Section 1 presents an overview of the current challenges related to the management of urban water supply systems. Based on these, case studies are selected for empirical testing of the proposed methods, concepts and frameworks. Existing approaches are briefly summarized, and the guiding research questions and objectives of this dissertation are introduced. In Section 2 the concepts of urban water security, resilience and sustainability are explored, and methods for their quantification are proposed and applied to seven urban case studies. The Capital Portfolio Approach (CPA) proposes four "capitals" needed to secure urban water supply services, and the fifth, "community adaptation" replaces services, when public services are insufficient. The metrics proposed in the CPA are translated into model parameters, which are used to simulate and quantify urban water resilience. Sustainable management adds another dimension to the CPA, which considers local and global sustainable management of urban water systems. The results presented in Section 2 are supported by two manuscripts provided in *Appendix 1* and *2*. Section 3 presents an assessment of emergent patterns and processes leading to vulnerability, inequality and unsustainable practices, detailed aspects of which can be found in a third manuscript (*Appendix 3*). The different institutional-infrastructural setups of the seven case-studies leading to disconnections and invisibilities of urban water services are explored in the context of poverty and rigidity traps. Section 4 delves into the interfaces of hydrological, social-ecological and social-ecological-technical systems, and how our understanding of these can help manage urban water systems. The dissertation concludes in Section 5 with a discussion of implications for management and further research.

1.1 The Water World We Live In: Selection of Case Studies

Given the various challenges emerging from global change and the specific conditions surrounding each urban area, seven cities were selected representing a wide range of hydro-climatic and socio-economic conditions on four continents. Given these settings, the selected urban water supply systems' functioning is based on heterogeneous capacities and resource availabilities, as well as varying constraints challenging supply services. They serve as test cases and examples for the application of the proposed concepts, frameworks and models.

1) Singapore, Melbourne and Berlin are representative of highly developed cities in many places of Northern Europe, North America, Australia and parts of Asia. They have adapted to constrained conditions resulting from internal pressures and external stressors and have had the necessary resources to do so. Each of them is faced with a different set of environmental constraints: The island-state of Singapore has a limited, but hydrologically productive land area. Local sustainable water management was promoted early-on, and it is known today as one of world leaders in water innovation and technology (Khoo, 2009). Singapore is dependent not only on water imports from neighboring Malaysia, but also much of its demand for food and energy resources, as well as manufactured products are imported (Hausmann et al., 2013). Melbourne is faced with recurring flood and drought conditions, and recently launched its transformation from conventional, supply-oriented management towards water-sensitive urban design triggered, among others, by citizens who opposed the managers' supply-oriented strategy in response to a thirteen year drought (1997-2010) (Ferguson, Brown, Frantzeskaki, et al., 2013). Limited regional competition for land and water resources allow the city to access large amounts of resources and build water storage and production facilities. Surrounded by industrial legacy landscapes and open-pit mining, Berlin's urban managers are required to carefully monitor and manage the risk of source water quality impairments (IGB, 2016).

2) Chennai (India) and Ulaanbaatar (Mongolia) are representative of cities facing multiple threats and pressures, lack the necessary resources for change, and are characterized by large slum populations, similar to many cities in Africa, Asia, Central and South America. Chennai's water supply is highly variable in its spatial distribution, and the frequency, quality and volumes of delivery (Srinivasan, 2008). Chennai's citizens proved highly resilient during a drought in 2003/2004, during which piped water supply was completely switched off. As the coldest capital

city in the world and set in a semi-arid climate, Ulaanbaatar (Mongolia) is particularly challenged in supporting a growing urban population (Myagmarsuren et al., 2015). Its early function as a monastery and trading post in a predominantly nomadic state was first replaced by a socialist version of a modern capital, then boosted by international capitalist investors interested in the exploitation of the country's natural resources and busted by economic crisis (Diener & Hagen, 2013). Besides its climate and water scarcity, it is challenged to provide water services to a population of which 60% are not directly connected to public infrastructure (Myagmarsuren et al., 2015).

3) Amman (Jordan) and Mexico City represent transitional cities. Already one of the most water-scarce cities in the world, Amman is additionally challenged by rapid population growth, which is driven by repeated waves of incoming refugees from neighboring countries. This challenges urban managers to maintain an infrastructure that is strained by rapid urban change and intermittent supply (Ray et al., 2012; Rosenberg et al., 2008). Today one of the largest urban areas in the world, Mexico City has struggled for centuries to subsist in an unfavorable environment prone to flooding, droughts and earthquakes (Tellman et al., 2018). Yet, driven by rural poverty and attracted by the promise of their share of urban economic growth, growing numbers of population raise the demand for urban water services (Lankao & Parsons, 2010). Inequality of urban water security is high (Eakin et al., 2016) with implications regarding water access, affordability, hygiene and health, as well as negative feedbacks leading to violence (Watts, 2015).

1.2 Addressing the Urban Water Challenge

The goal of this dissertation is a deeper understanding of the dynamics of urban water supply security, resilience, and sustainability. The evolution of cities and societies in their natural and engineered environments is empirically assessed in terms of their current state (security), dynamic behavior (resilience) and past or potential future trajectories driven by (un-) sustainable management. The following questions guide my research:

1) How do natural, human and engineered system elements interact in shaping the behavior of urban water systems?

2) What are the constraints of and limits to urban water security, resilience, and sustainability?

3) What can we learn from generative mechanisms and patterns found in nature, and similar patterns in human and engineered systems forming through space and time, about how to manage CNHE systems?

4) What are the determinants of the long-term evolution of human-water systems?

5) How can we navigate the trajectories of urban water systems?

The coupled systems investigated here comprise water resources ("natural"), urban managers, decision-makers and citizens ("human"), and urban water supply infrastructure ("engineered"). The interaction between natural and human systems in the urban context is mediated through engineered systems, which become a critical element in the human-nature relationship. Services of urban water supply are assessed as systems that reach into their complex, regional and global environments, and interact with other sectors, such as sanitation and drainage, but also food and energy supply. Empirical data from the case studies are used for assessments of local conditions and individual system trajectories. Local-scale assessments are embedded into a comparative framework that provides a global perspective. The approach integrates quantitative and qualitative data and information retrieved from global data bases, as well as from key stakeholder interviews and household surveys. The mix of methods includes conceptual frameworks that inform more focused modeling studies, and the interdisciplinary nature of this thesis requires drawing from various fields, such as hydrology, engineering, governance, economics, etc. This yields insights into how globally comparable conditions play out differently due to variations in human response (management decisions and priority setting) and local adaptive capacity, resulting in large heterogeneity across case studies.

2. "Healthy" Urban Water Supply Systems

[A version of this chapter will be submitted for review to a scientific journal.]

Urban water security, resilience and sustainability are three important, and heavily debated concepts. Although they are set as targets to be achieved by policy and management efforts around the world (UN-Habitat, 2017; UN, 2018; UNISDR, 2017), there are no agreed-upon methods to measure their achievement. The conceptualization and methods for their quantification are the subject of on-going scientific research and debate (Costanza et al., 2015; Arjen Y Hoekstra et al., 2018; Meerow et al., 2016; Sampson, 2017; Spiller, 2016). Thus, the list of current efforts mentioned in the introduction, including the Sustainable Development Goals and urban resilience initiatives, read like visions of overall healthy societies; it remains up to local governments to decide how to achieve them.

After the recognition of the "limits to growth" (Meadows et al., 1972) the *Brundtland Report* on sustainable development was published in 1987 (WCED, 1987), from which four primary goals are derived: 1) Ecological sustainability, 2) the satisfaction of human needs (eliminating poverty), 3) intra-generational (redistribution from over-consumers to the poor) and 4) inter-generational equity (safeguarding resources for future generations, including the reduction of population growth) (Holden et al., 2014). These goals include aspects of security and sustainability. I refer to "security" as the current state of system functioning, and the satisfaction of human needs and intra-generational equity belongs in that category. Ecological sustainability and inter-generational equity on the other hand refer to future impacts, marking the sustainability category. The notion of "resilience" was later introduced, when the need to prepare for and respond to global change and natural hazards became a global priority (Brown, 2014).

While the three terms are often used interchangeably, here I provide distinct definitions of the three and propose that the security, resilience and sustainability of urban water supply systems build upon one-another as illustrated in **Figure 1** below. The security of the objective function (here: urban water supply services) focuses on the local, present conditions of the water sector, and therefore has clearly defined spatial, temporal and sectoral system boundaries (blue triangle at the top).

Resilience refers to the ability of the system to absorb and recover from shocks, to adapt and transform in order to maintain its functions. This emergent property describes the dynamic response to shocks and disturbances, which can result from interdependencies across scales and sectors. Recovery from shocks requires the mobilization of resources, which are often drawn from outside the boundaries defined for system security. For example, in the case of an emergency, such as an earthquake or a humanitarian crisis, resources are mobilized from national or international sources, that are not accessed during usual operation of the urban water system, and are therefore not considered in a performance assessment of urban water security. While the evaluation of urban water security may consider average values or assess the system as a snapshot in time, the persistence during and recovery from other shocks, such as droughts, requires buffering capacity, e.g. drawn from diverse water sources, which are allowed to replenish in the absence of shocks. This stretches the spatial and temporal scales of resilience into regional and longer-term boundaries, and requires the consideration of inter-sector dependencies, such as the water and energy sectors.

Finally, sustainability is considered a process and its most broadly accepted definition is that of sustainable development put forward by the Brundtland commission: *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." (WCED, 1987). Since then, variations of this definition have been proposed, and criticism about the details of the report abound. The sustainability definition used here follows the discussions laid out by Costanza et al. (Costanza et al., 2015). Its scope expands that of the Brundtland Commission in that it comprises not only a temporal dimension (with local focus), but puts the system boundaries at global scale and incorporates cross-sector interactions. A sustainable system therefore is one that synergistically co-evolves with its environment (across scales and sectors) with global optimization towards net zero impacts (see details in Section 2.3). Sustainability, represented in Fig. 1 as the base of the triangle, cuts across sectors, as well as spatial and temporal scales:

Temporal scales: Unsustainable management of resources in the past challenges urban water security in the present, and unsustainable management today challenges urban water security in the future.

Sectors: Unsustainable decisions made in other sectors, such as the energy sector (e.g., introduction of power plants with high cooling water demands in the face of climate change and increasing water scarcity) or in industry (e.g., processes with high pollution potential) may threaten water resource availability or quality for urban supply now or in the future.

Spatial scales: Externalization of environmental costs is not a sustainable solution, as system boundaries are drawn at a global scale and do not allow such externalization, which will come at the cost of people and ecosystems elsewhere, now or in the future.

A “healthy” urban water supply system therefore is one that provides secure urban water supply services to all citizens without compromising its ability to respond to shocks and disturbances, as well as without compromising ecosystem functioning and the well-being of future generations anywhere on the planet.

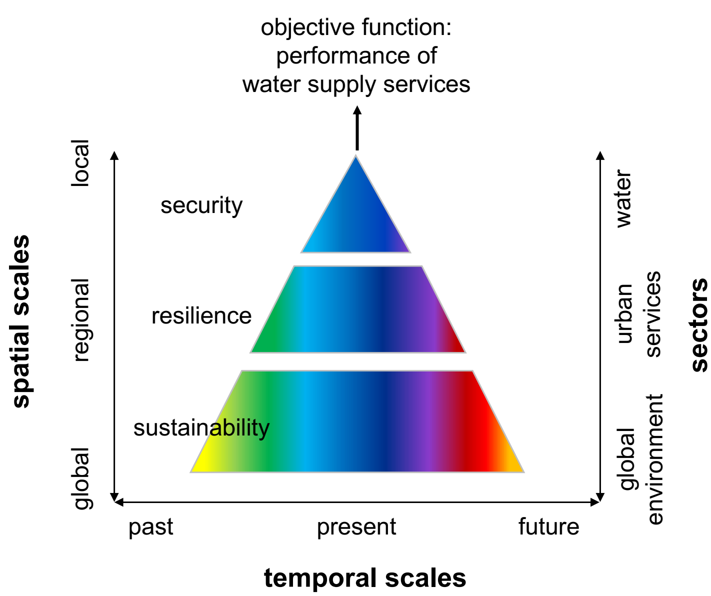

Figure 1: Cross-scale and cross-sectoral framework of urban supply security, resilience and sustainability.

In the following, urban water supply systems are assessed as an example of complex CNHE systems. I propose methods for the quantification of the three concepts of security (an objective function), resilience (short-to-medium-term system behavior in response to shocks) and sustainability (long-term, cross-scale and cross-sector impacts and trajectories resulting from (un-) sustainable management practices). Urban water supply security and resilience have been investigated in detail in two of the attached manuscripts (***Appendices 1*** and ***2***), and I only briefly summarize those aspects and results that are relevant for the following sections.

2.1 Security

[A version of this chapter has been published in Global Environmental Change (Krueger et al., 2019)*].*

Two hypotheses guided the research of this section: 1a) *Urban water security determined by the abundance of water resources at the city scale can be undermined by the lack of additional "capitals" necessary for providing urban water services to citizens. These capitals are: infrastructure, financial capital and management power.* 1b) *Where public services are insufficient, community adaptation significantly improves urban water supply security.*

Common assessments of urban water security quantify the average per capita water availability (Damkjaer & Taylor, 2017; Floerke et al., 2018; Jenerette & Larsen, 2006; McDonald et al., 2014; McDonald, Douglas, et al., 2011; Padowski & Jawitz, 2012), or focus on the sections of urban society living in water poverty (Cho et al., 2010; Eakin et al., 2016; Juran et al., 2017; Srinivasan et al., 2010b; Sullivan, 2002; Wutich et al., 2017). Based on a comparative assessment of 108 cities in Africa and the US, 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. Only 7% of investigated cities remain insecure, due to minimal ability to access local and/or imported water. 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 resulting from 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. However, such assessments do not consider urban water insecurity caused by inadequate water quality, issues of access, affordability, reliability, etc. Such issues are taken into account in the investigation of urban water poverty, but are often limited to single case studies or qualitative assessments (Cho et al., 2010; Eakin et al., 2016; Juran et al., 2017; Srinivasan et al., 2010b; Sullivan, 2002; Wutich et al., 2017).

The concept of urban water supply security used here combines these different perspectives, moving beyond the estimation of water availability at the city level, and proposes an integrated, quantitative and comparative approach that defines urban water supply security based on the services that citizens receive, including access, safety, reliability, continuity and affordability, as well as the perceived risk to these services (Krueger et al., 2019). Such holistic approaches have been investigated for individual case studies (Eakin et al., 2016; Srinivasan et al., 2010a; Wutich et al., 2017), but have not been applied in cross-city comparisons, and have not developed suitable frameworks that would allow application and comparison across cities.

Dynamic changes to water resources due to the variability of climate, land use changes and resulting variability in water availability, degradation of infrastructure, population growth and changes in demand, as well unexpected shocks, such as floods, droughts, contamination events, etc. require urban water systems to be adaptive. I propose here, and as elaborated in Krueger et al., (2019) and ***Appendix 1***, that urban water security results from the interaction of five types of capital. Four capitals contribute to public water services at the city scale: 1) urban water resources (W; average available volume per capita), 2) the status of infrastructure (I; household connection rates, leakage, and delivered water quality), 3) management power (P) resulting from efficient and accountable governance systems with adequate institutional complexity, 4) financial capital (F) for building, maintaining and operating the water system. The fifth capital is the adaptation of the community (A) to insufficient public water supply services (access to additional water supplies, bridging of supply gaps resulting from intermittent services, in-house treatment of supplied water). Public water services resulting from the interaction of the four capitals is expressed by the public Capital Portfolio: $CP_{public}= \{W,I,F,P\}$, and total water services, including the adaptive response of the community is $CP_{total} = CP_{public}+A$. The quantification of the five capitals, robustness and risk, as well as the resulting, integrated water security estimation is done following the Capital Portfolio Approach (CPA), as proposed in *Appendix 1* (Krueger et al., 2019), and results are summarized in Fig. 5 (Section 2.3) as part of the extended CPA.

Figure 2 shows estimations of urban water supply security for seven global urban case studies. Water security is represented by values of the capital portfolios (CP) of public services and, where public services do not meet demand, total services (CP+A), which include adaptation ("self-services") of the community. Calculations of water security based on the CPA are plotted against the ratio of urban water availability over demand for water provided by the public utilities (UWA/D_W) and including additional water accessed by households ($(UWA+ W_{extra})/D_W$). 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 that are described in the case studies in *Appendix 1.* They include issues such as lack of household connection (access), intermittent supply (continuity), unreliability of services, inadequate water quality, safety issues for accessing water services (e.g., at public wells or from tanker trucks) and unaffordably high prices.

The difference between water security achieved through public services (CP_{public} = CP, circles) and total services (CP_{total} = CP+A; dots) illustrates the role of community adaptation in 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 highlights the fact that cities with low CP (+A) are water insecure (red), while a high CP (+A) indicates water security. Intermediate CP (+A) indicates the transition zone.

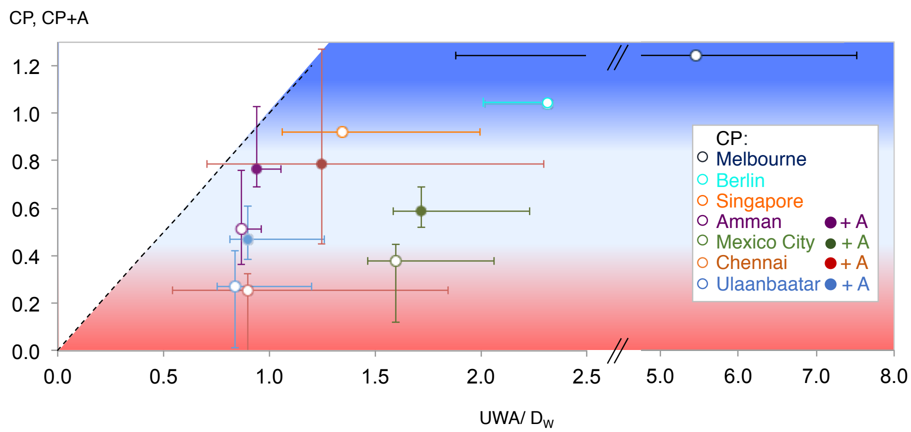

Figure 2: Comparison of two water security metrics for seven global cities based on 1) CPA assessments ("services", see text; y-axis) and 2) the ratio of water availability and demand (x-axis). Circles represent public services (CP and W_{public}/D) and dots represent total services (CP+A and W_{total}/D). Error bars are ranges around the mean indicating inter-annual variability and data uncertainty.

Community adaptation significantly improves urban water security. However, the ability to adapt is highly variable across and within cities (see Section 3.3 for intra-city assessment of Amman case study). For the two cities with lowest CP_{public}, Chennai and Ulaanbaatar, in Chennai the community contributes the majority of water services, resulting in high CP_{total}, while in Ulaanbaatar CP_{total}, i.e., total water security, remains low, due to constrained adaptive capacity of the community in addition to low $CP_{public.}$

The CPA takes into account uncertainty by estimating error ranges based on data uncertainty and inter-annual variability of the five capital metrics. The quantification of water security using the CPA is aggregated at system scale (here: city scale), and distinguishes water security generated by the public entities and community adaptation (A). Community adaptation in fact emerges in the aggregate from a heterogeneous distribution of individual households, which have varying capacity for adaptation.

Risk and robustness elements are also quantified in the CPA (for details see *Appendix 1*, (Krueger et al., 2019) and Fig. 5). The interplay of the three dimensions (capital availability, robustness, and risk) generate dynamic system behavior: capitals and their robustness allow the public entities to adaptively manage the system in response to shocks, while households adapt to varying levels of services. These three dimensions of the CPA are used as input in a systems dynamics model for the quantitative assessment of system resilience, as described in Section 2.2 below.

2.2 Resilience

[A version of this chapter has been submitted for review to Earth's Future.]

Two hypotheses guided the research of this section: 2a) *Urban water system resilience in response to recurring shocks emerges by mobilizing capital robustness, which marshals and recovers the capitals needed for system functioning.* 2b) *Communities enhance urban water resilience by coping with unexpected shocks.*

Resilience has been defined as the ability of a complex adaptive system to absorb shocks, to adapt and to reorganize in order to maintain system functions (Gunderson & Holling, 2002; Walker et al., 2004). Resilience of urban water supply services refers to the dynamic behavior of the system in response to disturbances. We propose that resilience is an emergent behavior resulting from the availability of capitals and their recovery marshaled through system robustness (Krueger et al., n.d.). Resilience requires constant adaptive management, and is contingent on the timing and magnitude of shocks (Klammler et al., 2018). Resilience of urban water security is assessed using a systems dynamics model proposed by Klammler et al. (2018). Non-dimensional, coupled systems dynamics of service deficit ($0 \leq \Delta(t) \leq 1$) and service management ($0 \leq \mathrm{M}(t) \leq 1$), aggregated at the city-scale are described as follows:

$$\frac{d\Delta}{dt} = (1-\Delta)b - a\mathrm{M}\Delta + \xi \qquad (2.1)$$

$$\frac{d\mathrm{M}}{dt} = (1-c_1\Delta)\mathrm{M}(1-\mathrm{M}) - \mathrm{r}\frac{\mathrm{M}^n}{\beta^n+\mathrm{M}^n} - c_2\xi \qquad (2.2)$$

where growth in service deficit ($(1\text{-}\Delta)b$) is determined by demand growth and service degradation (rate constant b), and recovery ($aM\Delta$) is determined by service management and an efficiency coefficient (constant a). Stochastic shocks (ξ) lead to increases in service deficit, and are modeled as outcomes of a Poisson process, with mean frequency (λ) and exponentially distributed magnitude of mean value (α). A logistic function describes the replenishment in the capacity of service management (M, Eq. 2.2), and it is limited by coupling with Δ through c_1. For $c_1 \rightarrow 0$ the two systems are increasingly decoupled. The maximum relative depletion rate (r) determines degradation of M following a Langmuir function (Langmuir, 1918). Two parameters, β and n, characterize the scale and shape of the depletion curve in M, respectively. The coupling parameter c_2 determines the direct shock impact on M. These model parameters are derived by translating the CPA (capital availability, robustness and risk) into suitable model parameters, which are quantified using empirical data for the seven case study cities. Details on the model and the method of parameterization are presented in *Appendix 2* (Krueger et al., n.d.). The model produces time series of Δ and M, and state-phase diagrams for assessing system behavior regarding resilience. Examples are shown for Mexico City and Amman in **Figure 3**.

The significance of community adaptive response found in the CPA is made explicit in the comparison of public services (Fig. 3c-d) and total services (Fig. 3e-f). Total service management levels are significantly improved, the magnitude of shock impacts reduced and recovery after shocks is accelerated as a result of community adaptation. Comparison of Fig. 3g-h and Fig. 3i-j) shows that stable states are at higher service and management levels for total services (g-h) compared to public services (i-j), with changes in response dynamics in the M-Δ relationship. Surprisingly, all seven cities result in a single stable state for urban water security (Fig. 3g-j). As indicated in Section 2.1, community adaptation is the aggregated emergent response of all urban households. However, adaptive capacity is typically highly variable among households or for different districts within a city, as is water supply. This adds to system complexity and inequality, which is elaborated in *Appendix 2* and further explored in Section 3.3.

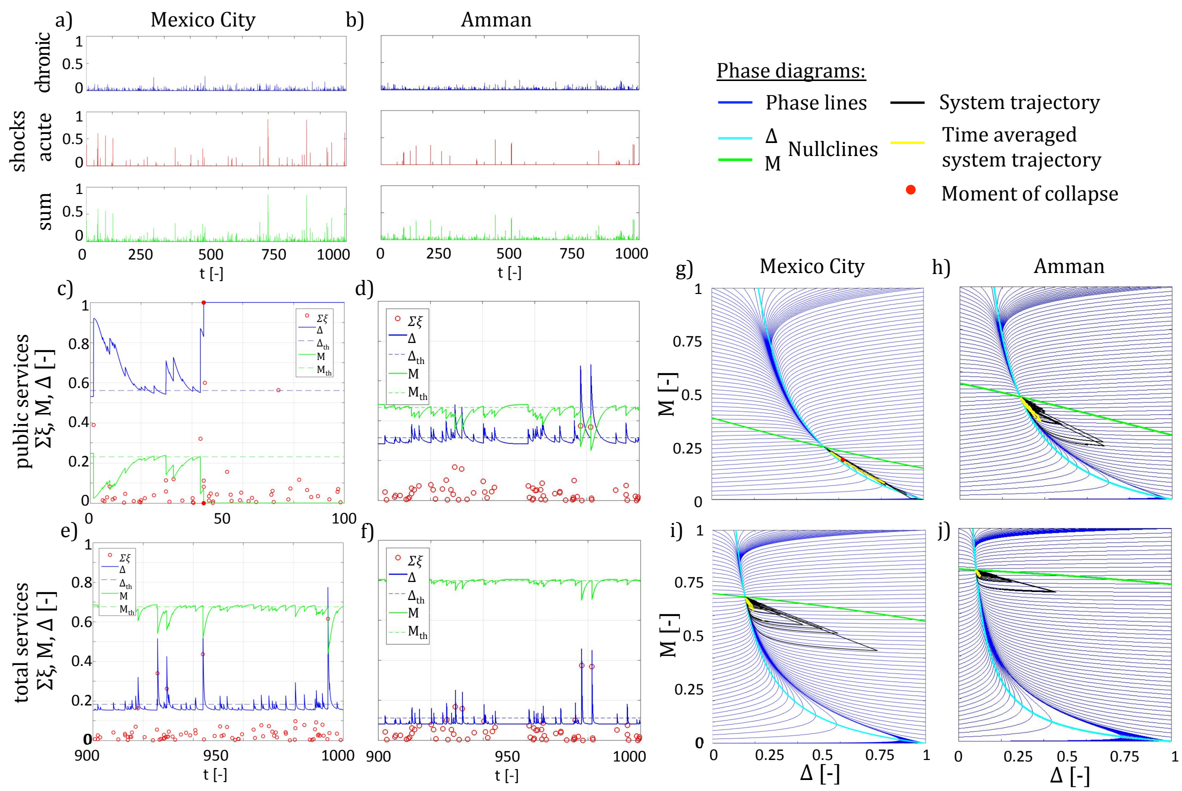

Figure 3: Model simulations for resilience analysis of Mexico City and Amman. a-b) Shock time series for 1000 time units; c-d) Time series of shocks (Σξ), service deficit (Δ) and adaptive management (M) for public water supply services. e-f) Same time series as in c-d) for total services (including community adaptive behavior). g-h) and i-j) are state-phase diagrams showing the stability behavior with a single stable state for each case, black lines are system trajectories in response to shocks.

Figure 4 summarizes the resilience of the seven case study cities. The resilience landscape of urban water supply security represents the surface spanned by fixed points of water supply service deficit generated by the model, resulting from combinations of CP (CP+A) and robustness across their entire value ranges. Fixed points are stable points for public and total service deficit in each case study, respectively. Stable points are system "attractors", towards which systems evolve in the absence of shocks. Arrows pointing down from the fixed points indicate the impact and response to recurring shocks and disturbances: Arrow length represents maximum impact magnitude on adaptive management, and is a measure of the system's capacity to absorb shocks; arrow width is proportional to mean crossing times of service deficit above a certain threshold (expected mean service deficit), and is a measure of the rapidity of service recovery after shocks (Klammler et al., 2018; Krueger et al., n.d.).

Robustness (RP) is critical in maintaining resilience, and no fixed points exist for RP $\lesssim$ 0.3. For cities with low CP, small differences in RP can be crucial for maintaining services (albeit at low level), as can be seen from comparison of public services in Chennai and Ulaanbaatar. In general, the results indicate that security (represented by CP, RP and risk) and resilience (system dynamics represented by ability to absorb and recover form shocks, i.e., arrows in Fig. 4) tend to co-evolve.

Recovery of shocks is slow for cities with low resilience (wide arrows for Ulaanbaatar$_{public}$, Mexico City$_{public}$ and Ulaanbaatar$_{total}$). No arrow for Melbourne's water system indicates a decoupling of water service deficit from the dynamics in service management: Managers have access to high levels of capitals and robustness, so that shocks have no impact on management capacity. Short and thin arrows indicate strong buffering capacity and fast recovery.

The results above combined with the behavior for the seven cities examined using Monte Carlo simulations (1000 model simulations x 1000 time units) indicate that there are three categories of resilience regimes: 1) water secure and resilient cities, which immediately recover from recurring shocks (Melbourne, Berlin, Singapore), 2) water insecure and non-resilient cities, where shocks quickly lead to system collapse (Chennai$_{public}$, Ulaanbaatar), and 3) cities in transition with varying response to shock regimes (Amman, Mexico City).

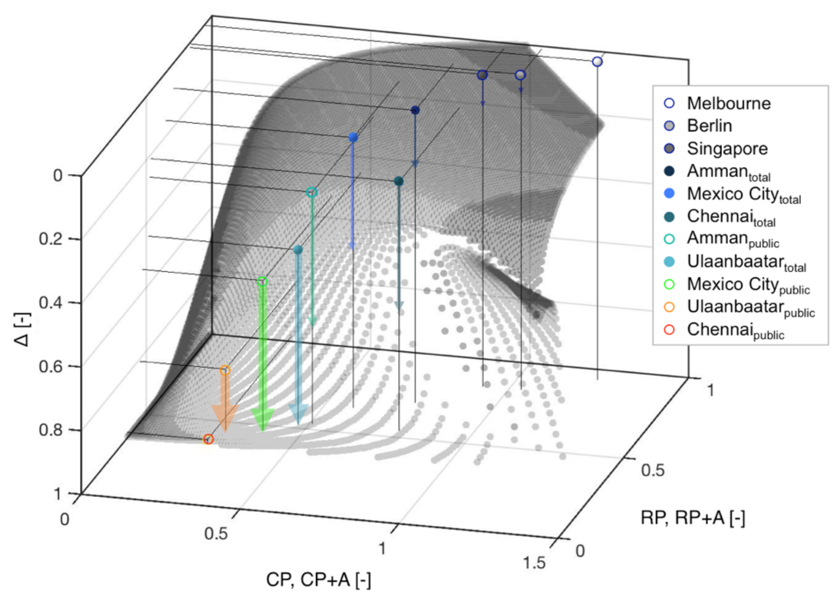

Figure 4: Resilience landscape of urban water supply services. Grey dots are fixed points for all possible parameter combinations. Circles and dots are fixed points of urban case studies, arrow length is maximum impact of shocks on adaptive capacity, and arrow width is mean crossing time above the expected service deficit level. For details see *Appendix 2*.

2.3 Sustainability

[A version of this chapter will be submitted for review to a scientific journal.]

"*It took Britain half the resources of the planet to achieve its prosperity; how many planets will a country like India require?"* Mahatma Gandhi, cited in (Costanza et al., 2015)

Seventeen goals have been set forth in the form of the United Nations Sustainable Development Goals (SDGs), all of which are to be achieved in the spirit of the Brundtland Commission, in which the needs of the present are achieved without compromising the ability of future generations to meet their own needs (WCED, 1987). According to the Brundtland report and the SDGs, the goals can only be achieved by harmonizing three elements: economic growth, social inclusion and environmental protection. The first of the three elements is what has sparked criticism (Costanza et al., 2015), because instead of fostering the well-being of all (meeting the needs set forth in the goals), economic development, equaled to the growth of GDP, is put first priority (without correction for inequality) (United Nations, 2015a), which has the potential of corrupting the achievement of all other goals. Another definition is suggested as *"Sustainability is the process of living within the limits of available [...] resources in ways that allow the living systems in which humans are embedded to thrive in perpetuity"* (University of Alberta, 2010). Here, "*in perpetuity*" is essential and requires, as proposed in Section 2, net zero impacts achieved through global optimization of a sustainable system that synergistically co-evolves with its environment (across scales, sectors and cities).

Therefore, with a distinct definition of the terms security, resilience and sustainability, sustainability's focus then is on the (cross-scale) impacts of practices on nature (ecosystems and water resources) and on humans (inter-generational or different groups of society) (Costanza et al., 2015). Sustainability requires that trade-offs be avoided between different short-term and long-term, local and global goals. Here, I propose that sustainability emerges from the way in which security and resilience are achieved. Differences in *how* urban water security, resilience, and sustainability are achieved determine their long-term limits and constraints. Note that this is not intended as a new definition of sustainability, but a re-interpretation from individual sustainability goals at the local scale to the avoidance of trade-offs (or integrated achievement) at the global scale, and re-focusing on the required "balance" among social, environmental and economic goals of well-being today and into the future. Where "global" and "into the future" demands that impacts are reduced to net zero.

Sustainability therefore is largely a matter of management options, priorities and decisions. Because of the long-term perspective of sustainability, trade-offs across scales and sectors play a critical role, in particular across the strongly interconnected sectors of water, energy and food ("water-food-energy nexus").

For urban water security, sustainability implies the protection of water sources and downstream water bodies (quantity and quality), as well as any ecosystem directly or indirectly contributing to the "production" (filtering, storage, etc.) of water resources that are currently in use or may be used in the future. Air, soil, and water pollution can impact water quality through point and diffuse sources in the long-term, as impairment of ecosystems impacts the self-purification capacity of river, soil, and groundwater. Ecological and water footprints (Borucke et al., 2013; Hoekstra & Mekonnen, 2012) account for these effects. In addition, from a socio-political perspective, maintaining good relationships with neighbors and other water resource users (upstream or downstream) (Folke et al., 2005; Janusz-Pawletta, 2014), and keeping population growth at a sustainable level are important factors in maintaining sustainability (Costanza et al., 2015; Lambin & Meyfroidt, 2011; Meadows et al., 1972; Rockström et al., 2009).

An emerging field in the scientific literature assessing sustainability issues investigates the long-term impacts of climate change adaptation measures and strategies that are *mal*adaptive (Barnett & O'Neill, 2010; Juhola et al., 2016; Marlow et al., 2013). Researchers in this field specifically focus on *"action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups"* (Barnett & O'Neill, 2010). Categories of maladaptation have been defined including the rebounding and shifting of vulnerability, as well as the erosion of sustainable development (Juhola et al., 2016). This important field of research will reveal a range of unsustainable practices implemented under the veil of sustainability. This research prominently demonstrates that the long-term, inter-sectorial, and inter- as well as intra-generational impacts of measures taken here and today can often only be determined in retrospect ((Costanza et al., 2015) p. 121), as feedback effects often do not come into effect immediately and alter processes and impacts in the long-term (Henderson & Loreau, 2018; Lafuite & Loreau, 2017). Because of unforeseen feedback effects that act across sectors and system boundaries, interdisciplinary, coupled system perspectives are critical in sustainability assessments (Bai et al., 2016; Blythe et al., 2017; Lafuite & Loreau, 2017).

This leads me to making two propositions: 1) *The way in which a system function (here: water supply security and resilience) is achieved determines its sustainability*; 2) *Sustainability should be assessed both locally and globally*.

As a basis for estimating urban water sustainability, I assess the different management types present in the seven case study cities. The management portfolio (MP) presents an extension of the CPA framework introduced in Section 2.1 and *Appendix 1,* and is added as a dimension to the availability, robustness and risk of the five capitals. Sustainable management is assessed for each of the five capitals: Water resources (W, "natural capital"), infrastructure (I, "physical capital"), financial capital (F), management power (P, "political capital"), community adaptation (A, "social capital"). In analogy to the quantification of capital availability, robustness and risk (*Appendix 1,* (Krueger et al., 2019)), sustainable management metrics for each capital (M_W, M_I, M_F, M_P, M_A) are quantified using aggregated scores across several indicators that take values 0-1. Externalized environmental costs produce negative values. Aggregation of the sustainable management indicators across all five capitals are determined for local sustainability (MP_{local}) and for global sustainability (MP_{global}). The latter includes external footprints.

Indicators for the assessment of sustainable management include the current footprint of water management and consumption patterns locally and globally, as well as management options towards improved sustainability of the five capitals, which impact water security and resilience evolution in the future. Examples are the coordinated management of services across urban sectors (e.g., sanitation, drainage, energy, mobility, etc.) and the engagement of the community to maintain awareness and a certain degree of connection between citizens and the ecosystems, infrastructure and institutions providing urban water services. The resulting Management Portfolio (MP) can be used as a starting point for the development of future scenarios of sustainability. Some of the metrics, including the national water and ecological footprints, as well as demographic control measures, assess the global impact of human activity on the environment. Others, such as the urban water reach or the fraction of recycled water are city- and sector specific. These metrics have a certain degree of overlap, and are included to differentiate between global and local sustainability, to consider cross-scale and cross-sector perspectives, as well as to get a more specific estimation of city-scale water management for sustainability. Details of the sustainable management assessment method are described in *Appendix 4*.

Figure 5 presents the characteristic water system profile of capitals (black), robustness (blue), risks (red) and management portfolios (green) for the seven urban case studies. The CPA introduced in *Appendix 1* discusses the first three dimensions and I focus here on the portfolios for sustainable management (MP). Green lines indicate global management sustainability for each capital, while dashed lines are for local factors. Local/global lines only differ for W and A, as only these capitals include factors contributing to global sustainable management (MP_{global}). In contrast to the portfolios of capitals, robustness and risk, which for all capitals are >0, management sustainability can be <0, where negative capital management represents externalized costs.

Water secure and resilient cities (Singapore, Berlin, Melbourne) show a relatively sustainable local management portfolio, for example, low internal WFP and low WD lead to high M_{Wlocal}, however large external water and ecological footprints produce strongly negative $M_{Wglobal}$. Half of Berlin's WFP is virtually exported (54% internal versus 46% external WFP), and its EFP exceeds global biocapacity by 190%. In spite of major efforts towards becoming a water-sensitive city, M_{Wlocal} is low in Melbourne. Urban hinterland uninhabited by humans allows relatively unconstrained access to such resources, which leads to large WD (Viggers, 2017).

Negative values for $M_{Wglobal}$ are highest in Ulaanbaatar and Melbourne, which both have large per capita ecological and water footprints. According to Mekonnen and Hoekstra (2011), Mongolia has one of the largest per capita water footprints, resulting from import dependence for a large range of products, a large green water footprint (rainwater consumed in agricultural production) due to low agricultural water productivity and high meat consumption. However, the authors note that data insecurity may play an important role in this outcome (Mekonnen & Hoekstra, 2011).

F is relatively sustainably managed in Singapore, Melbourne and Berlin. Lack of cost recovery in Ulaanbaatar, Chennai, Mexico City and Amman results in low M_F and Amman, Ulaanbaatar and Singapore are also dependent on foreign aid and/or investment.

While cities that can afford to, tend to externalize their environmental costs, the pattern is not consistent across cities. MP_{global} is less sustainable than MP_{local} in Singapore, Berlin, Melbourne and Ulaanbaatar, meaning that environmental costs supporting urban lifestyles are externalized. The reverse is true in Chennai, and to a lesser extent in Mexico City. Local management sustainability is lowest in Mexico City. In Amman, local and global MP are almost on par. Similar profiles to that of Chennai can be expected for economically less developed countries in India and Sub-Saharan Africa, in which local MP is smaller than global MP (largely driven by a small external WFP and negative EFP, i.e. positive biocapacity; in Chennai external WFP <2% of total WFP).

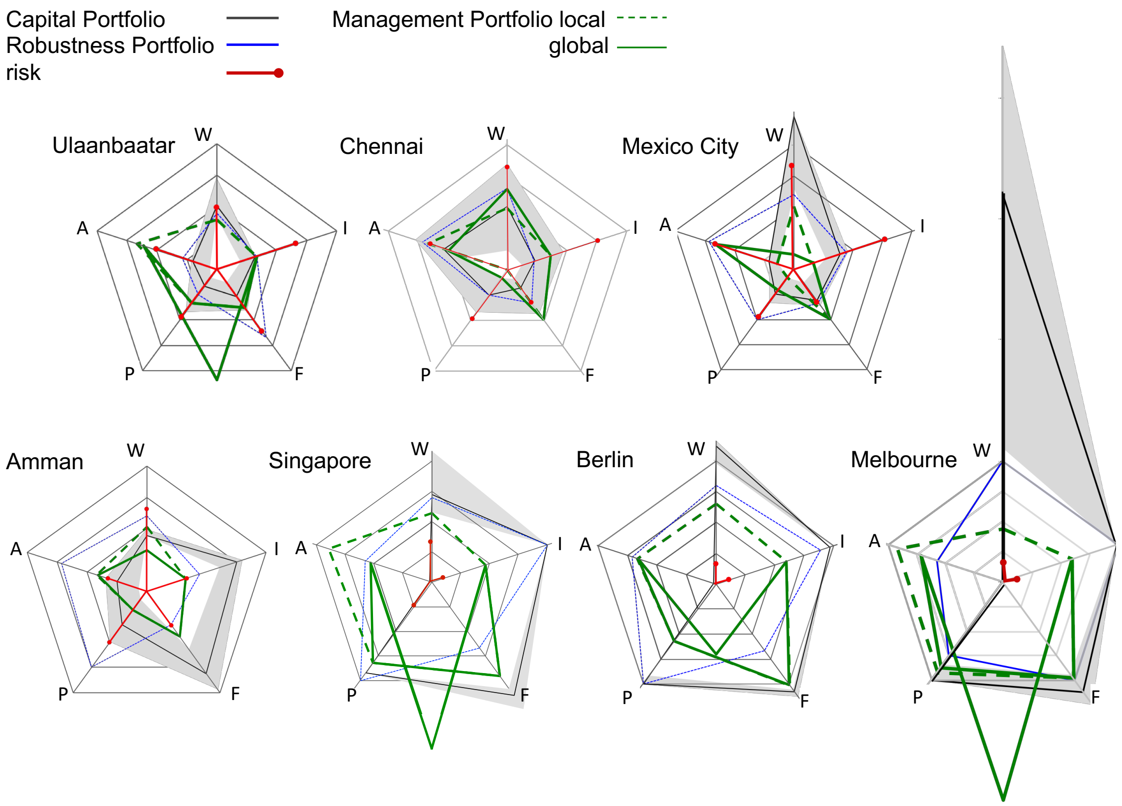

Figure 5: Water system profiles based on the CPA assessment with portfolios for sustainable management (MP). Adapted from (Krueger et al., 2019).

2.4 Balance

[A version of this chapter will be submitted for review to a scientific journal.]

As explained in Section 2.2, urban water resilience emerges from the interplay of capital availability, robustness and response to shocks. I propose here that, like resilience, sustainability is an emergent behavior of a complex system. Urban water sustainability will emerge as a result of a city's security, resilience, and the type of management decisions taken, as well as cross-scale and cross-system interactions ("Panarchy", see Section 4.4). Sustainability determines a city's future security and resilience, i.e. unsustainable practices today threaten the latter two dimensions in the long run. Thus, security, resilience and sustainability interact in a loop: water supply services need to be secure, before they can be resilient, and in order to be sustainable, they need to be resilient. The primary focus of each of these dimensions has a different scale: Security focuses on system functioning at the local scale (community/ city), resilience considers interactions of local and regional processes (e.g., external shocks and environmental changes impacting resilience), and sustainability looks at local and global scale impacts. Figure 6 illustrates this loop.

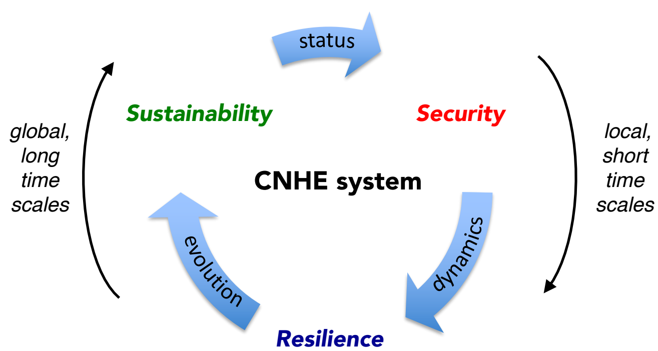

Figure 6: CNHE system dimensions loop.

While CNHE system functioning in response to changing boundary conditions and unexpected shocks requires all three dimensions, urban water systems are characterized by differing "balance" between the three. **Figure 7** illustrates the relative contributions of CP, CT and MP to balanced urban water supply systems in the seven case study cities. The capital portfolio (CP) as an indicator of security, the mean crossing time above mean service deficit (CT, corresponding to the inverse of arrow width in Fig. 4, Section 2.2) as an indicator of resilience and the management portfolio (MP) as an indicator of sustainable management. The shaded area in the center of the triangle is the *balanced* operating space, where security, resilience, and sustainable management are most balanced. Colors of data points indicate the level of water supply services produced from the systems dynamics model presented in Section 2.2. For example, Chennai's public water system (C) at the top left lacks resilience, and the red color indicates high service deficit (compare to Fig. 4). Although public services in Chennai score highest in MP, it lacks CP to gain security and CT to respond to shocks. Data used for the calculation of MP for the seven cities, as well as CP and CT values can be found in *Appendix 4*.

Fig. 7 also shows the balance of CP, CT and MP_{local}. It illustrates the dependence of cities on externalized environmental costs (i.e., the import of water-intensive and environmentally degrading products). For example, Melbourne, Singapore and Berlin appear in the balanced area for MP_{local}, however, they have large externalized environmental footprints (low MP_{global} values), which they can only afford as long as other cities' consumption remains below biocapacity, leaving enough resources for those cities to consume through virtual water imports / greywater exports. Ulaanbaatar's local management sustainability (UB_L) locates the city in a relatively central position of the ternary diagram. However, low urban water supply security makes this position unviable.

Required management directions are shown here by colored arrows: Systems positioned to the right of the shaded area should focus on improving water security (red arrows); cities to the left should focus improving system resilience (blue arrows), and cities below the shaded area should consider *how* their water, food and energy security is achieved, i.e., reduce their footprints, and work towards increased sustainability (green arrows). Comparison of UB and UB_L indicates the tension arising between local and global management goals: from a global perspective, UB should reduce its global environmental footprint, however it needs to invest heavily into higher security at the local scale (UB_L).

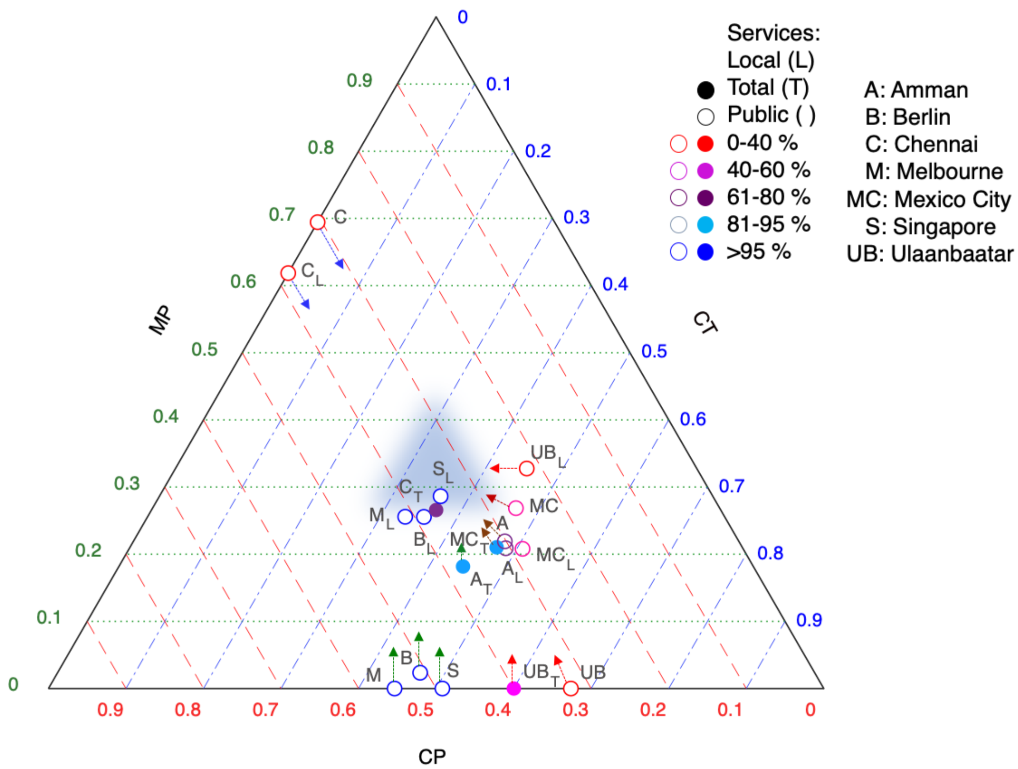

Figure 7: Relative contributions of CP, CT and MP to the balance of urban water supply systems Subscripts indicate total water services with global MP (X_T), local water services with local MP (X_L), and public services with global MP (no subscript). Arrows indicate the vectors for management trajectories towards balanced urban water supply systems.

Efforts towards water security in Amman include an additional long-distance water transfer project, in which water from the Red Sea is desalinated and transported (using fossil and nuclear energy sources) into the country's urban areas to meet growing demands (Coyne et Bellier et al., 2012). In addition, the country is planning to construct nuclear power plants for meeting its rising energy demands (Ramana & Ahmad, 2016), which will require reliable water supplies for cooling. However, instead of taking advantage of the mutual benefits that the water-energy nexus can have, e.g., by producing renewable energy from waste and sewage sludge, or producing recycled water by using locally abundant solar power, decisions are taken that foster the negative trade-offs of the water-energy nexus, i.e., constructing water supply schemes with large energy requirements, which are met from non-renewable sources, and building power plants with large water-demands, thus creating a vicious cycle of mutually increasing demands. Such management decisions in the water and energy sector will move Amman from its current position towards lower MP.

3. Emergent Patterns in Natural, Human and Engineered Systems

Resilience and sustainability are two themes that emerged from the investigation of ecosystems and human behavior, and the quest is here how these apply to coupled natural-human-*engineered* systems. Following the system level perspective in Section 2, here in Section 3, I take a look inside these systems, in order to understand what patterns and generative mechanisms may lead to resilient and sustainable CNHES. The question guiding the investigations in Section 3 is: *What can we learn from generative mechanisms and patterns found in nature, and similar patterns in human and engineered systems forming through space and time, about how to manage CNHE systems?* I start by an introduction of the fractal landscapes that characterize natural and human systems, and provide examples from urban water infrastructure analyses to show how these patterns also apply to such engineered networks (Section 3.1). This is followed by an investigation of the vulnerabilities emerging from the generic patterns and mechanisms, again by comparing social, natural and engineered systems. I provide another example from urban infrastructure networks to illustrate variations in these vulnerabilities (Section 3.2). In Section 3.3 different setups of institutions and infrastructure (urban social-ecological-technical systems, SETS) are presented for the seven case study cities, and compared to a framework proposed for the assessment of social-ecological systems (SES) from an institutional perspective. The complexity of urban SETS results in different levels of "invisibility" of services and disconnection between citizens and ecosystems, which is supported by data gathered in household surveys and key stakeholder interviews. In Section 3.4 I use the foregoing results for a discussion about poverty and rigidity traps and how they manifest in urban water systems.

3.1 Fractal Landscapes

[A version of this chapter has been published in Physical Review E (Krueger et al., 2017).*]*

Hypothesis 3: *As human-engineered systems, water distribution and sanitary sewer networks evolve to follow Pareto power-law node-degree distributions, similar to those found in natural and social networks.*

Complex networks of all kinds have been shown to evolve to power-law distributed node-degree and rank-size distributions, including, but not limited to, social interaction networks (Guimerà et al., 2003), neural networks in the brain (Batista et al., 2010), rank-size distributions and production functions of cities (Córdoba, 2008; Lobo et al., 2013), stream orders in river networks (Paik, 2006; Yang et al., 2017), scientific collaboration networks (Barabási et al., 2002), road networks (Kalapala et al., 2006; Masucci et al., 2014; Strano et al., 2012), traffic flows (Zhan et al., 2017), and functional hierarchies of water distribution and sewer networks (Klinkhamer et al., 2017; Krueger et al., 2017; Yang et al., 2017; Zischg et al., 2017). These distributions follow the power-law scaling described by the simple relationship (Eq. 3.1):

$$p(k)=ak^{-\gamma} \qquad (3.1)$$

where $p(k)$ is the probability of node-degree (or rank size) (k), and the exponent (γ) is the characteristic scaling parameter. The power-law is sometimes tempered or truncated, depending on the size of the network, and in this case described by either a double power-law with two characteristic exponents describing the trunk and the tail of the distribution, respectively (Eq. 3.2), or by exponential tempering (Eq. 3.3):

$$p(k_{trunk})=ak_{trunk}^{-\gamma trunk},\ p(k_{tail})= bk_{tail}^{-\gamma tail} \qquad (3.2)$$

$$p(k)=ak^{-\gamma}e^{-ck} \qquad (3.3)$$

Figure 8 shows results of network analyses of water distribution and sanitary sewer networks for a large Asian city. Fig. 8a) presents the temporal evolution of the sanitary sewer network over a 45-year period. Fig 8b) shows the water distribution network, emphasizing different pipe diameters. Fig. 8c) presents water distribution zones. Zone delineations are used to create sub-networks, and their analysis supports the hypothesis of fractal scaling throughout the city as shown by the convergence of γ for all sub-networks. Analyses are conducted after conversion of the "primal", spatial map into a “dual”-mapped network graph based on hierarchical intersection continuity negotiation (HICN (Masucci et al., 2014)), for which pipe diameters are used to reveal capacity-based ("functional") network hierarchies (see ***Appendix 3*** for details). Fig. 8d-g) are results of the topological analysis of the dual-mapped networks: d) a double power-law characterizes the topology of the entire sanitary sewer network; e) comparison of sanitary sewer (red) and water distribution network (blue); f) convergence of node-degree distributions with increasing network size towards γ_{trunk}=2.45±0.27; g) breaking point (k_{break}) between the trunk and tail of the distributions increases with network size; outliers indicate network vulnerability (see Section 3.2 below). Details on the topological network characteristics in the spatial and temporal evolution of the water distribution and sanitary sewer networks can be found in *Appendix 3.* This work shows unchanged scaling laws across space and time throughout the city's temporal and spatial evolution, and that deviations from the general network patterns can lead to vulnerabilities and increased network failures (Krueger et al., 2017).

The power-law distributions are indicative of two phenomena: 1) "Scale-free" nested hierarchies characterize the network structures leading to few large and highly connected "hub" nodes, and many small nodes with few connections. 2) These hierarchies are a result of preferential attachment of new nodes to already well-connected, large nodes, amplifying the hierarchical effect. They are "scale-free" only within the bounds of system size, leading to a truncation of the heavy tail of the distribution; space and information constraints lead to an effect of "partial" preferential attachment, in which new nodes attach to the nearest, largest node (Carletti et al., 2014).

A fractal landscape emerges that structures the world through hierarchical networks of all kinds and at all scales. Power-law distributed urban infrastructure networks are embedded in power-law structured cities (Batty, 1994, 2013) that support power-law structured activities and production functions (Bettencourt et al., 2008; Bettencourt et al., 2010; Bettencourt & Lobo, 2016; Lobo et al., 2013). Outside cities, fractal trees inhabit landscapes that also show this type of fractal scaling, as demonstrated for the size-distribution of vegetation patches (Kéfi et al., 2007), and wetlands based on a digital elevation model (Bertassello et al., 2018).

Not all networks follow this power-law behavior, but those that do benefit from certain efficiency and robustness characteristics in the resulting structures and functions (Albert et al., 2000; Gao et al., 2016; Rodriguez-Iturbe et al., 1992; Solé & Montoya, 2001). Increasing truncation of the power-law indicates functional disruptions to natural and engineered fractal-like networks, such as grazing pressures leading to desertification (Kéfi et al., 2007) or road traffic leading to congestion (Zhan et al., 2017). Excessively heavy tails can indicate emerging network vulnerability, as I will elaborate in Section 3.2 below.

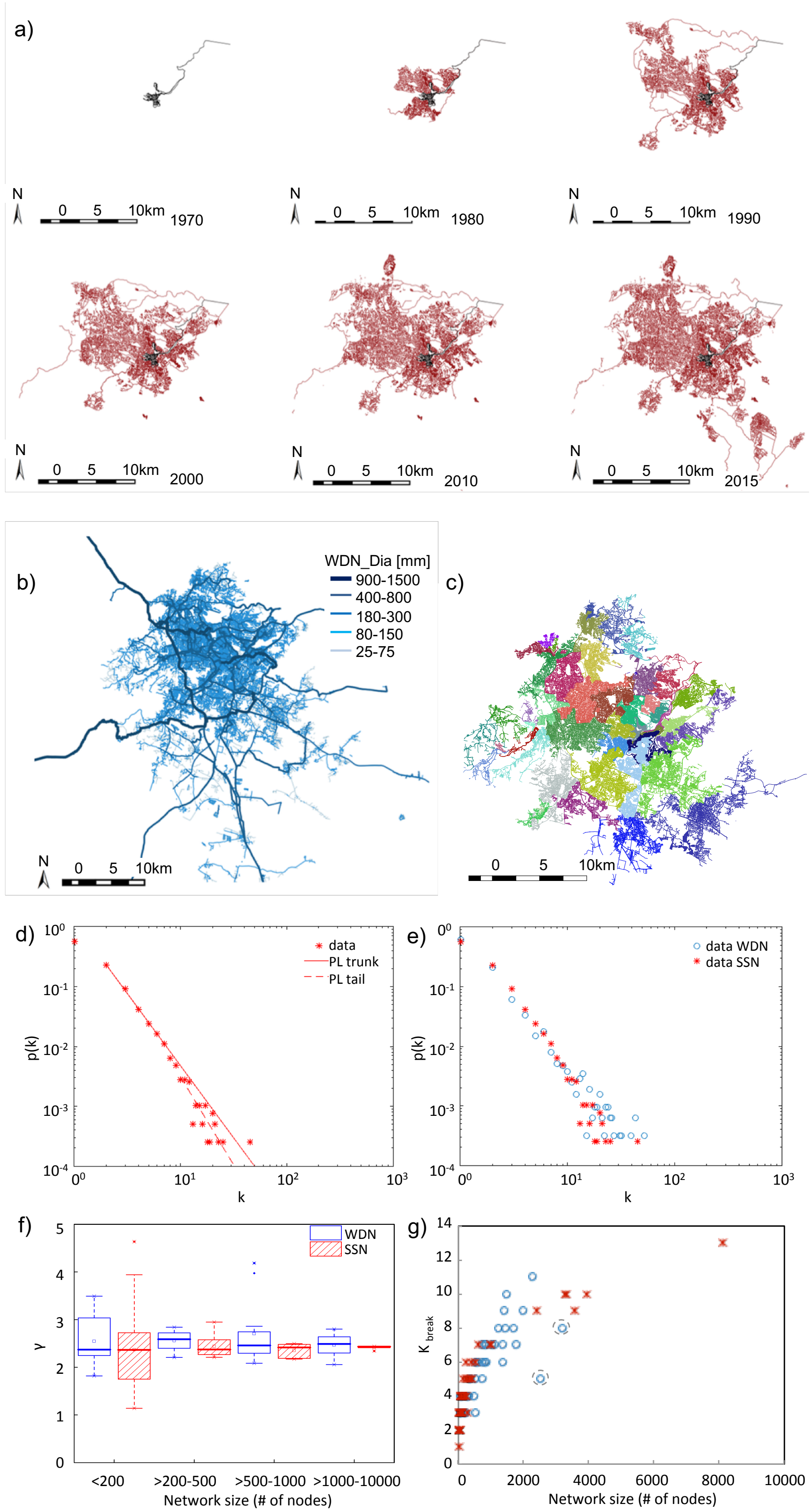

Figure 8: Spatio-temporal evolution of water distribution and sanitary sewer networks. Source: (Krueger et al., 2017) except Fig. 8c).

3.2 Inequality and Scale

[A version of this chapter will be submitted for review to a scientific journal.]

Hypothesis 4: *Functional efficiency of networks requires Pareto power-law node-degree distributions. Deviations from such distributions indicate 1) functional constraints for distal tempering and 2) network vulnerability for "flat tails"*.

Dynamic systems and networks without space, information, regulatory or other growth constraints increasingly build up to form giant hierarchical networks, in which failure of hubs can lead to a collapse of the entire connected network (D'Souza et al., 2014). Temporal dynamics follow these generic patterns, too: Occurrence of shocks, such as earthquakes, landslides, forest fires, financial market crashes and electric power grid failures are highly unequally distributed and have heavy-tailed, power-law event size and frequency distributions (D'Souza et al., 2014). These temporal dynamics can exacerbate the disaster magnitudes, as long periods with only small disruptions allow systems to build increasingly larger, highly connected networks. When one of the large events hits, the potential for damage in very large, highly connected networks is several times higher than in smaller systems.

To illustrate the vulnerability of scale-free networks to large-scale disaster and collapse, I analyzed the robustness of different types of "scale-free" networks, characterized by variations in the power-law distributions of their node-degrees. **Figure 9** provides a visualization of the spatial maps (Fig. 9a), the network graphs (Fig. 9b-c) and the node-degree distributions (Fig. 9d) of three sub-networks of an urban water distribution system. The pronounced "hub-spoke" structure characterizing network 11 can be clearly seen in the graph depiction (Fig. 9b), and results in the "heavy tail" of the node-degree distribution (Fig. 9d).

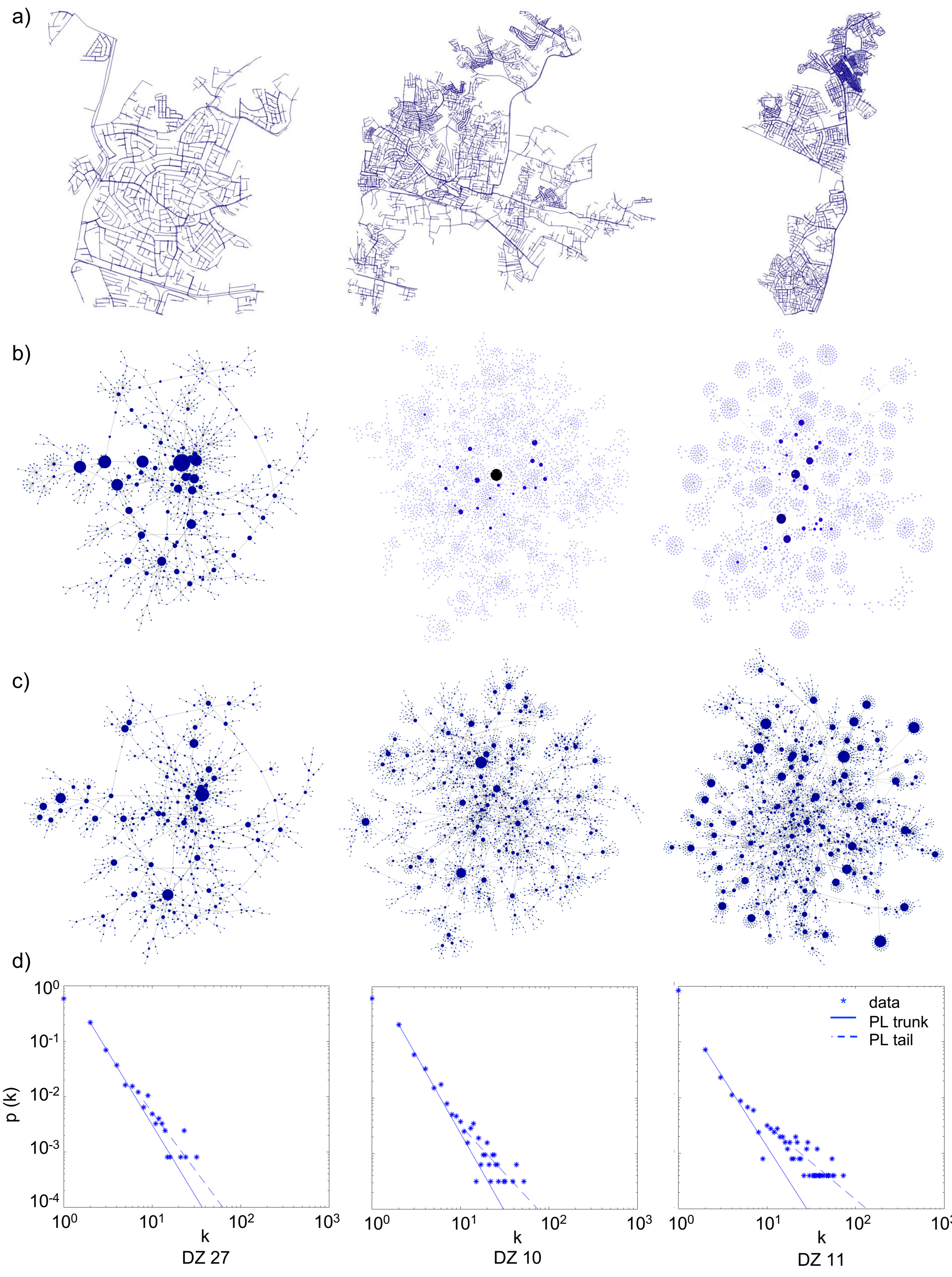

Figure 9: Water distribution network topological properties for three heavy-tailed distributions. a) Spatial maps; b) network graphs with node size corresponding to betweenness centrality; c) node size corresponds to node-degree; d) node-degree distributions described by: DZ27: k_{break} =8, $p(k)_{trunk}$ =1.35k$^{-2.64}$, $p(k)_{tail}$=0.74$k^{-2.15}$, n=1241 (dual mapped nodes); DZ10: k_{break}=8, $p(k)_{trunk}$=1.46k$^{-2.8}$, $p(k)_{tail}$=0.26$k^{-1.88}$, n=3179; DZ11: k_{break}=5, $p(k)_{trunk}$=0.4$k^{-2.49}$, $p(k)_{tail}$=0.09$k^{-1.47}$, n=2425.

Box 1: Inequality and Scale in Nature and Society

The scaling laws that determine the structure and function of real-world networks are also characteristic of income (Dragulescu & Yakovenko, 2000) and wealth distributions within societies, as well as species distributions in ecosystems (Scheffer et al., 2017). In economies, the links can be thought of as financial transactions among actors. However, instead of the accumulation of links in a node, resources (e.g., wealth, biomass, etc.) are accumulated in a few actors (individuals/social groups or species), while the majority accounts for only a small portion of resource accumulation. These scaling laws signify inequality in resource distribution, which is more extreme for wealth than for income (Dragulescu & Yakovenko, 2000; Scheffer et al., 2017; Yakovenko, 2013). The processes leading to such inequality are 1) differences in competitive power of the actors and 2) chance. The reason that chance plays a major role is that once even just a small difference between actors occurs, the gap grows larger through multiplicative growth, i.e., gains and losses are multiplied by actual wealth (Scheffer et al., 2017).

Inequality in nature is regulated, among others, by influx of population numbers contributing to the maintenance of small species populations (additive growth), through the cycles of the seasons or through predators and other natural enemies, including diseases (Fortin et al., 2005; Scheffer et al., 2017; Smith et al., 2003). In societies, the main equalizer of economic inequality is taxation. Although economic growth and disasters, such as major wars, can change the level of inequality, the association of wealth and power facilitates further enrichment through wealth-protecting institutions (e.g., absolute property rights and the right to inherit) (Scheffer et al., 2017).

An important mechanism undermining wealth-equalizing institutions is societal upscaling. A historical analysis of wealth distribution in Western Europe during the Middle Ages shows that inequality was limited by the size of local communities, which constrained opportunities of transactions, and of land and capital accumulation. The "*growth of international trade, migration and inter-regional labor and capital markets, as well as [...] the processes of state formation with the rise of more centralized bureaucracies [....] (triggered) a long episode of rising inequality*" (Scheffer et al., 2017). This period was followed by a phase of wealth-regulating institutions during the 19th and 20th centuries. However, over the past decades, globalization has removed many of these constraints. Opportunities for wealth accumulation are now global, and regulating institutions at this scale are lagging behind (Scheffer et al., 2017).

In an analysis of scaling laws describing the relationship between the per capita GDP and urban population sizes for European cities, Bettencourt et al. (Bettencourt & Lobo, 2016) suggest that, according to the urban scaling laws, European cities remain below their size potential. If Europe promoted the development of large megacities their GDP could be multiplied by a factor of 1.3 per capita for cities in the order of >50 million inhabitants. Regardless of what this would mean in terms of resource extraction to maintain such an "economic colossus" (Bettencourt & Lobo, 2016) and what kind of living conditions might be found in such megacities, knowledge about consequences for 1) the rise of inequality for lack of adequate regulatory institutions, and 2) the potential for cascading disasters as a consequence of system complexity and size, promoting cities to follow scaling-laws to their theoretical limits seems highly questionable. This is particularly true, as the same authors also suggest that the pace of life increases with city size and the resource constraints putting a limit to unbounded growth need to be overcome by technological innovations at increasingly faster pace. Once innovation cannot keep up with the accelerating cycles of growth, collapse is unavoidable (Bettencourt et al., 2007).

The robustness of scale-free networks refers to random failure of network nodes or links (Albert et al., 2000). They are, however, highly vulnerable to failure of network hubs (Solé & Montoya, 2001), as shown in **Figure 10**. Response differs between removal of node-degree (ND) hubs (Fig 10a) and betweenness centrality hubs (Fig. 10b). Betweenness centrality (BC) is a measure of the number of shortest paths linking any two nodes in a network, which pass through a given node. Removal of such nodes leads to rapid system collapse. Although networks 10 and 11 have similar ND distributions, their response differs significantly, with network 11 being more robust to ND hub deletion, but least robust to BC hub deletion. Response is similar for networks 11 and 27 for ND hub removal, whereas network 27 is most robust to BC hub removal. Note that network sizes differ, with DZ27<DZ11<DZ10. The network with the "heaviest tail" (and medium size) turns out to be least robust to BC hub removal, and the largest network ("intermediate tail") is most sensitive to ND hub removal. The smallest network with the "shortest tail" turns out to be the most robust to both kinds of "targeted attack". While this is a small network sample, networks 10 and 11 were selected based on the "outlier" character found for k_{break} values shown in Fig. 8g). Discussion of results shown in Fig. 8 with the local water utility confirmed that these were two of the zones with significant operational failure occurrence.

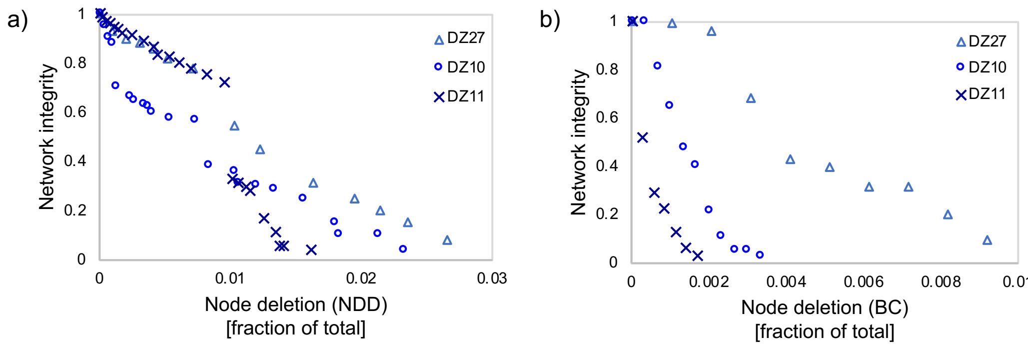

Figure 10: Stress-testing of three networks using hub-removal based on a) node-degree (NDD) and b) betweenness-centrality (BC). Network properties provided in captions of Fig. 9.

This demonstrates that network response and failure after targeted attack is highly variable among heavy-tailed, power-law network distributions. While limiting size can act as a regulator of inequality, uncontrolled growth, in particular when leading to pronounced "hub-spoke" structures (heavy tails) bears increased risk for catastrophic failure. An excessively heavy tail indicates that a large number of households is serviced by a single pipe, which, in the case of failure, affects a large number of people. Depending on the diameter of the pipe, this can bear the risk of blocking of a sewer pipe, if flow exceeds pipe capacity. In water distribution systems, if the main pipe is too small in diameter (but high ND and/or BC), this can lead to pressure loss in the terminal nodes (house connections). Alternatively, if the water main pipe is of large capacity, unregulated flow pressure can lead to bursting of smaller pipes. In either case, the efficiency gain that results from adding many terminal nodes to a hub requires additional control measures, such as pressure valves, loops (for redundancy), high density of isolation valves for emergency measures. Careful monitoring of quality standards becomes necessary, as large portions of the population will be affected by the failure of a single hub or contamination event, similar to the failure of hubs in economic systems (e.g., excessively large banks). I therefore suggest that simple analysis of the shape of the power law distribution indicates 1) functional limitation due to size constraints or network degradation indicated by tempering as shown with exponential tempering of the tail of traffic flow distributions (Zhan et al., 2017) degradation of ecosystems as shown for grasslands under grazing pressure (Kéfi et al., 2007), or 2) risk of failure due to excessively heavy (flat) tails (oversized hubs and excessive inequality), indicated by a double power-law, where $\gamma_{tail} < \gamma_{trunk}$.

Ecological networks protect themselves, through self-organization, by developing modular structures (Nordbotten et al., 2018) that buffer the propagation, and thus, the extent and total magnitude of shock and node or link failure impacts on the entire network (Gilarranz et al., 2017). Such modularity is also a design principle for engineered networks, such as water distribution networks, in which individual zones can be isolated from the network by closure of valves (Agathokleous et al., 2017; Ozger & Mays, 2004). In urban water systems, network size is constrained by three factors: 1) the location of the source (for water distribution systems) or sink (the wastewater treatment plant), 2) population distribution (as points of service demand), and 3) topography. Although drainage networks can cross watershed boundaries, the largest urban drainage networks draining to a single treatment plant are in the order of 10^3 km^2 (Yang et al., 2017). Thus, the extent to which drainage networks will cross watershed boundaries depends on the economic trade-off between the energy demand for pumping and the economic cost of constructing additional wastewater treatment plants. Therefore, although upscaling of treatment plants is usually economically more efficient than constructing additional plants (Rodriguez-Miranda et al., 2015), economic trade-offs result in large cities typically having several wastewater treatment plants. The evolution of an urban sanitary sewer system draining into one, then two and three outlets can be seen in Fig. 8a) above. The emergence of multiple outlets (year 2000: extended line to the East; year 2015: new sub-network extending South) indicates incremental decentralization as the network grows and as a result of efficiency trade-offs.

The same is true for water distribution networks, which are designed to optimize between the need for pumping/pressure regulation (allowing gravity-driven flow and constrained by topography), and the delivery of water from the source to the demand nodes, which leads to modular network design that is divided into distribution zones, such as in the urban area analyzed above (Section 3.1 and *Appendix 3* (Krueger et al., 2017)). Water import networks, on the other hand, quickly cross watershed boundaries beyond economic efficiency limits, driven by the pressure to access additional water sources. Long-distance water-import dependent cities eventually are faced with sustainability issues, either due to competition for resources as demand increases (Floerke et al., 2018), or due to environmental response to the management of flow variability, as explained in Section 3.4 below. These sustainability and competition issues are likely one of the reasons, why over the long history of European city evolution, unconstrained scaling laws, as expected by Bettencourt et al. (2016) are not observed.

3.3 Urban (Dis-) Connections

[A version of this chapter will be submitted for review to a scientific journal.]

There is great variability in how "urban areas" are defined across and within countries (United Nations, 2005). In most cases, definitions are based on the fraction of the working population employed in the agricultural sector, population concentration, or on legal grounds. Population thresholds for urban areas range from 200 in Greenland to 50,000 in Japan, and some countries define urban areas as localities with "urban characteristics" such as streets, electric light, water supply and sanitation systems. According to the UN Statistics Division *"The traditional distinction between urban and rural areas within a country has been based on the assumption that urban areas, no matter how they are defined, provide a different way of life and usually a higher standard of living than are found in rural areas."* (United Nations, 2018).

Cumming et al. (2014) characterize "urban" by the systematic development of infrastructure and institutions, as well as professional specialization aimed at advancing technology. The authors suggest that a growing population and increasing demand lead to the exploitation of ecosystems at increasing geographic extent, which results in a disconnect between humans and the environment and the over-exploitation of ecosystems. The authors describe urban and rural systems by two different conceptual models, the rural "green loop", where people directly interact with ecosystems to access ecosystem services, and the urban "red loop", in which people have an increasing demand for non-ecosystem services, which are met through regional socio-economic systems.

Here, urban areas are defined by the role of urban infrastructure in mediating human-environment interactions, including but not limited to, access to water, food and energy. Urban infrastructure is defined as infrastructure built and operated by a central authority or company, meaning that the provision of services is outsourced from the citizen to the entity operating the infrastructure. So, independent of where a person lives, the "way of life" in terms of the human-environment interaction for meeting basic and other demands has "urban characteristics". Direct interaction of humans and the environment for service provision are insignificant, which is in contrast to individuals or groups of people, who build, operate and maintain whatever technology or infrastructure they require to directly access ecosystem services.

The institutions literature, led by E. Ostrom, has put forward principles for sustainable resource management in social-ecological systems (Ostrom, 1990). Ostrom's sustainable management principles for common-pool resources (CPR) in social-ecological systems (SES) have achieved a high level of agreement among researchers from various fields. Such principles are lacking for urban systems, in which the relationship between humans and nature is mediated by complex infrastructural-institutional setups, and the provision of ecosystem services to humans is outsourced to a centralized entity. There is little understanding about how such principles can be applied in urban systems, or how they need to be modified in order to achieve sustainable management of CPR used in urban systems. For example, what does participatory governance in urban systems look like? The difference between SES and urban social ecological-technical systems (SETS) needs to be recognized in order to address the role of complex intermediary infrastructure and institutions that tend to disconnect people from ecosystems and produce invisibility of service efforts. Adapting the institutional design principles, such as, for example, polycentric governance, would require not only changes in the institutional design, but also the transformation of the co-dependent infrastructural (physical) design into modularized systems organized in nested hierarchies.

To illustrate the differences between SES and urban SETS, I compare the infrastructural-institutional setups of rural ("green loop") versus urban ("red loop") systems. Anderies et al. (2004) propose a framework for assessing the robustness and sustainability of such systems in terms of institutional setups, in which the link to infrastructure is made explicit, and thus representing a social-ecological-*technical* system (see **Figure 11a**). The authors assume "public infrastructure" to be a relatively simple system, and do not refer to complex urban infrastructure, which makes their system comparable to Cumming's rural "green loop" (Cumming et al., 2014). In this type of system, resource users are directly connected through bi-directional links to the resource, the public infrastructure and the public infrastructure providers, as indicated by arrows pointing in both directions.

Urbanization changes the structure of the SES with two major consequences: 1) The direct connection of resource users to the resource is interceded by infrastructural and institutional setups (Cumming et al., 2014). 2) A growing population and increasing use of technology turn the local CPR into a global CPR (Stern, 2011). The combination of the two leads to a shift in the scale of the problem. The former implies that the feedback loop between resource user and resource is removed and externalized to a different entity. The latter implies that the question of sustainability is no longer local, but global, which removes the feedback loop even further from the resource user.

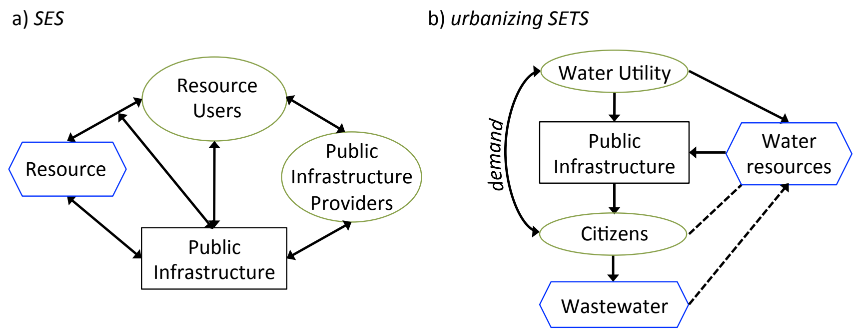

Figure 11: Stylized structures of rural (**a**) and urban (**b**) CNHES. Round shapes involve humans (i.e. self-organizing elements), squares are infrastructure (designed), and diamond shapes are resources derived from or available for ecosystem services. a) Adapted from (Anderies et al., 2004).

The conceptual structure of more complex, urbanizing SETS is presented in **Figure 11b**). In contrast to the rural SES, arrows are mostly uni-directional: the water utility (i.e., "public infrastructure providers") manages water resources and public infrastructure, which delivers water to citizens (i.e., "resource users"), who produce wastewater. Due to the lack of wastewater infrastructure, the latter risks contamination of the water resource, indicated by the dashed arrow connecting wastewater with the water resource. The only bi-directional link labeled "demand" indicates demand of the citizens for water supply services, which are directed to the water utility, and demand management directed from the utility to the citizens. Citizens' direct interaction with water resources is now interceded through infrastructure. As long as resources are exploited locally, e.g., from a local river, the dashed line indicates that citizens, although disconnected from direct interaction with resources, can still indirectly sense changes in water availability.

This very simplistic urban SETS framework changes as population and demand grows, and infrastructure and institutions evolve to maintain a balanced ratio of demand over water services. In densely populated areas, resources are shared and competed over with other users and cities. Additional infrastructure introduced to access or produce more water can create a growing distance and disconnect between citizens and water resources (Cumming et al., 2014). As Araral (2014) pointed out, such large-scale systems suffer from a “tragedy of the commons” (Hardin, 1968) and may require a revised set of management principles.

Figure 12 illustrates water system complexity of urban SETS structures for each of the seven urban case studies. Singapore, Berlin, Melbourne and Chennai have relatively simple SETS setups. In Chennai, while the utility accesses water resources and provides services to citizens through the public infrastructure, citizens also directly access a significant fraction of their water through private providers. They also access water from private wells on their properties, as indicated by the bi-directional arrow between citizens and water resources. In Singapore, wastewater is reused after treatment, which is shown by the loop created by linking wastewater through another public infrastructure node back to water resources. In the SETS framework for Berlin and Melbourne reuse of wastewater for the production of energy, fertilizer and irrigation/groundwater recharge is indicated by the link of the water system to the energy and food production systems.

In Ulaanbaatar, several governmental bodies are responsible for water resources (in the catchment), their extraction, and the provision to the urban distribution utility through the bulk water provider, adding several levels of hierarchy. This distances citizens further from the resource; feedback signaling water demand is passed on to the bulk water provider through the water utility. A dashed link between citizens and water resources indicates that Ulaanbaatar extracts its water resources from the local river (river filtrate), and the dashed arrow connecting wastewater and water resources indicates the lack of sanitary infrastructure in large parts of both cities, which poses the risk of contamination of ground- and river water.

SETS complexity is highest in Amman and Mexico City. Water extracted from multiple sources and distributed among multiple users/cities introduces an additional "human-engineered layer" between resources and citizens. Private water providers are added. In Amman, the bulk water provider, adding an institutional level of hierarchy, regulates private water providers through licensing. Urban water-related issues are decided on the level of the national government, and two water authorities are responsible for the monitoring and supply of bulk water. While in Amman wastewater is treated locally, it is not reused. In Mexico City, wastewater is moved out of the city, where it is used for agricultural irrigation without prior treatment. Drainage infrastructure is heavily degraded due to land subsidence, and frequent flooding causes sewer overflow, contaminating local groundwater, as indicated by the dashed line (Eakin et al., 2016). An additional node labeled "water access/production infrastructure" is added for both cities to highlight the fact that this infrastructure serves multiple major cities, accessing water brought into the urban area from afar. Infrastructure for water access/production serving a single city, only, is included in "public infrastructure" for all other cities. In Amman and Mexico City, local groundwater, as well as piped water are threatened due to 1) lack of and decrepit sanitary infrastructure, 2) water rationing causing pressure variation risking intrusion of contaminated water into water distribution pipes, 3) over-pumping.

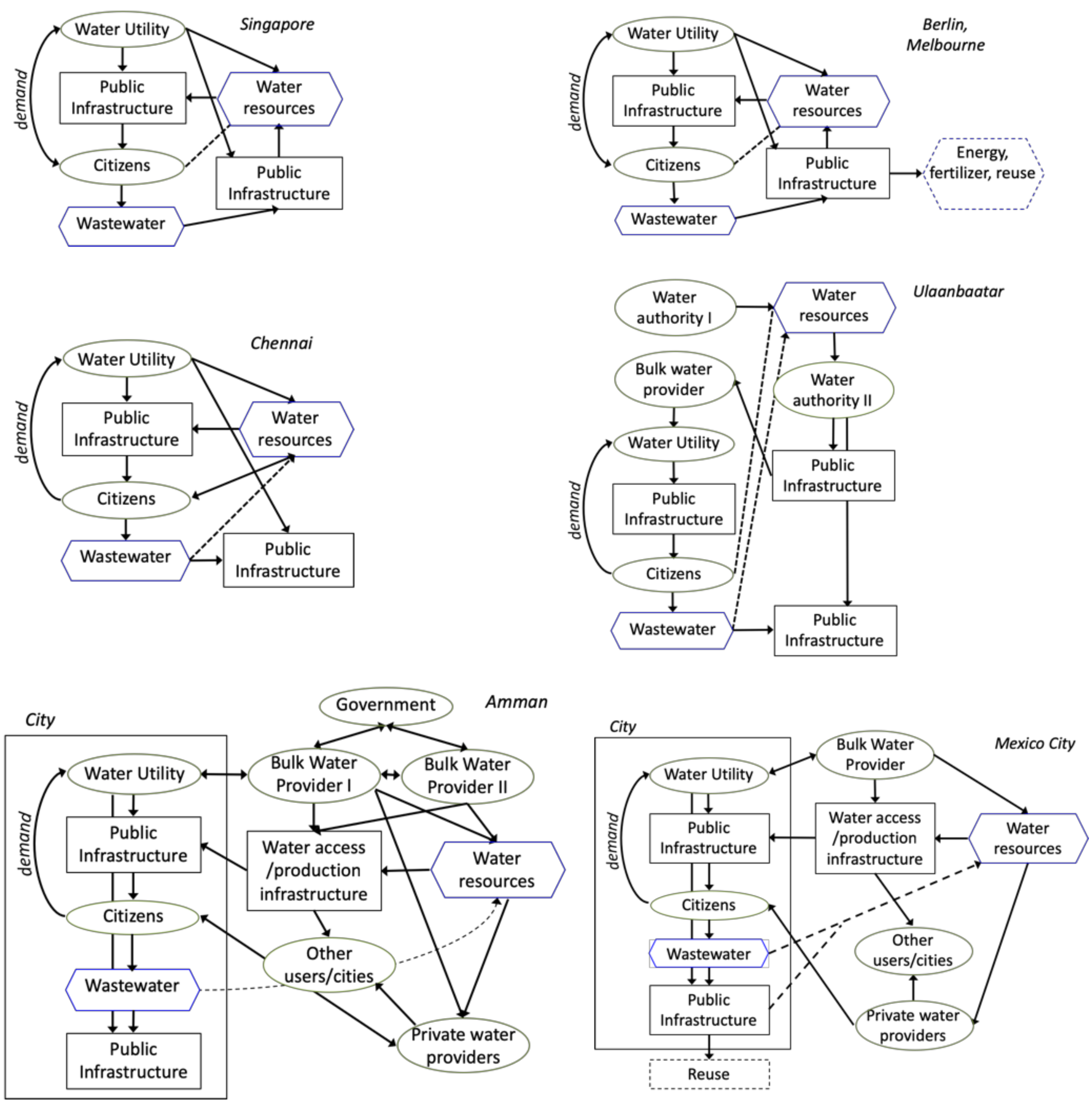

Figure 12: Stylized structures of urban SETS for the seven case study cities.

The disconnect between citizens and water resources with multiple mediators intercepting this direct connection requires that citizens' demand and the (eco-)systems providing water resources are properly managed. Bi-directional feedback loops between citizens and the entity managing the resource at the source is crucial, so that demand and long-term water availability can be balanced. The further removed water resources and citizens become, the more challenging it becomes to maintain these feedbacks. In addition, increasing urban complexity requires that cities adapt their internal management structures, in order to coordinate decision-making and operation across hierarchies and sectors (Osman, 2016; Wen et al., 2014). Note that the urban SETS structures shown in Fig. 11 and 12 are for water systems, only, and other sectors co-exist with similar structures and hierarchies, some of which are interacting and overlapping.

The urban SETS structures presented in Fig. 12 result from each city's efforts to: 1) Minimize service variability, 2) maximize efficiency and reliability, and 3) compartmentalize system functions and their management (e.g. water supply, sanitation, drainage, energy, food etc.). The former two give rise to complexity of urban SETS and lead to various "disconnections": While the water service system is made up of a large number of highly connected components with strong connections between citizens and the urban water infrastructure, this causes a disconnect between citizens and the ecosystems providing water resources. This disconnect is exacerbated by the minimization of flow variability and the maximization of performance and reliability, which lead to the "invisibility" of services, including infrastructure and ecosystems providing the resource. On the other hand, failure to provide services as demanded indicates a disconnect between citizens and infrastructure/water providers.

Compartmentalization is not always an intended process, but in rapidly growing cities results from the evolution of services in an unplanned manner, as well as from increasing complexity: Services are introduced sequentially, typically first electricity, then water supply, then sanitation and drainage, etc. Along with the incremental introduction of infrastructure comes the introduction of institutions for their management (Ashraf et al., 2016). Optimization of each system for its designed purpose can lead to tradeoffs. Tradeoffs and interdependencies makes management challenging, in particular regarding vulnerability to cascading failure (D’Souza et al., 2014; Klinkhamer et al., 2017). As a consequence, compartmentalization and interdependence then requires coordination among sectors, and a lack thereof can lead to increased resilience challenges (D’Souza et al., 2014; Lee et al., 2015). The subsequent integration of urban services and management by a single entity, such as in Singapore, Melbourne and Berlin, is a result of the overburdening need for coordination across multiple entities to ensure a range of critical urban services.

I propose here that: *Because in urban systems infrastructure intercedes the human-nature relationship, sustainable urban development requires careful management of connection, visibility and complexity.*

The evolution of urban SETS leads to three different but interlinked trajectories of 1) system complexity, 2) the visibility of services, and 3) the degree of disconnection between citizens and the ecosystems providing services. This is illustrated in Figure 13. Two alternate trajectories are drawn for each of the three dimensions, which capture the current status of the seven case study cities.

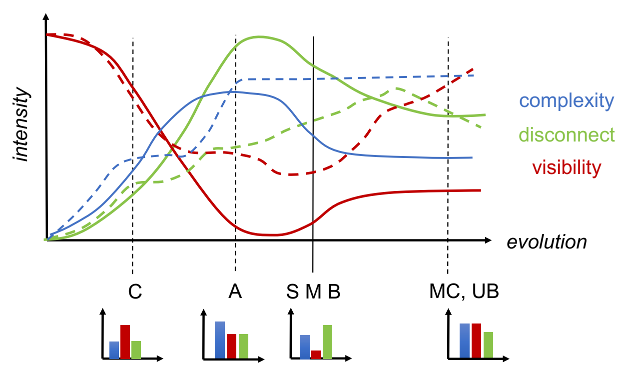

Figure 13: Evolution of urban SETS trajectories regarding system complexity, visibility of services and disconnection between citizens and water resources. Dashed trajectories and lines capture current state of Ulaanbaatar (UB), Chennai (C), Amman (A) and Mexico City (MC); solid trajectories and lines capture current state of Singapore (S), Melbourne (M) and Berlin (B). Profiles of current states are shown in bar plots below city initials. UB and C, and S, M and B share the same profile, respectively.

The number of nodes and links in the urban SETS structures shown in Fig. 12 are used as an indicator of system complexity. The visibility of services is linked to the performance of the water sector in providing services "unnoticed" to the consumer in terms of negative effects. Continuous supply of high quality water at household level makes the process of service provision "invisible". Service deficits, the lack of agency and the need to cope with inadequate services through the informal sector increases the visibility of services. Disconnection is a measure of the "distance" between citizens and the resource, and lack of awareness contributes to this effect. Therefore, complete invisibility leads to higher disconnect and decreases awareness (resulting in, e.g., profligate water use, discharge of contaminating substances into the sewer system and/or environment), etc., which is why water-sensitive cities strive to re-connect citizens with their natural environment as a "soft" management measure of demand and behavior (compare to sustainable management criteria in Section 2.3). In the case of strong, integrated urban water management, visibility and disconnect are mirror images of each other (solid lines in Fig. 13). However, the trajectories of visibility and disconnect become more variable in more complex urban SETS with weaker management power (dashed lines).

Assessment of water rationing and household survey data in Amman supports the notion of (in-)visibility of water services. Rationing and delivery of water on specific supply days requires citizens to carefully manage household water use (Gerlach & Franceys, 2009). Thus, this type of service deficit and its perception are indicators of service (in-) visibility. The spatial distribution of intermittent supply durations throughout the city, and community adaptive response are illustrated in Figure 14. Outlined districts in the map served as areas for a household survey, in which a total of 300 households were interviewed about water supply issues (survey questionnaire and details of the survey protocol are provided in *Appendix 5*). Boxplots show household storage capacity as one aspect of community response to rationed supply. Storage capacity varies widely, and shows no linear correlation with supply duration (Fig. 14b), but strong correlation with household income (Fig. 14c): Storage capacity increases with household income upto an income threshold of 350 JD cap-1. Above this threshold storage capacity drops off, which could result from the fact that higher income households are likely to compensate additional water needs by buying tanker water as needed, rather than increasing storage. 28% of surveyed households stated piped water supply volumes to be insufficient, with some variation across income groups (Fig. 14d). Fig. 14e) shows the results of the survey opening question, asking whether the respondent's household generally experienced water shortages, or other problems around water supply. Surprisingly, the majority (55%) answered "no" to this question (no trend with income), which shows how chronic service deficits in the form of weekly water rationing become part of a routine, rather than being perceived as a problem.

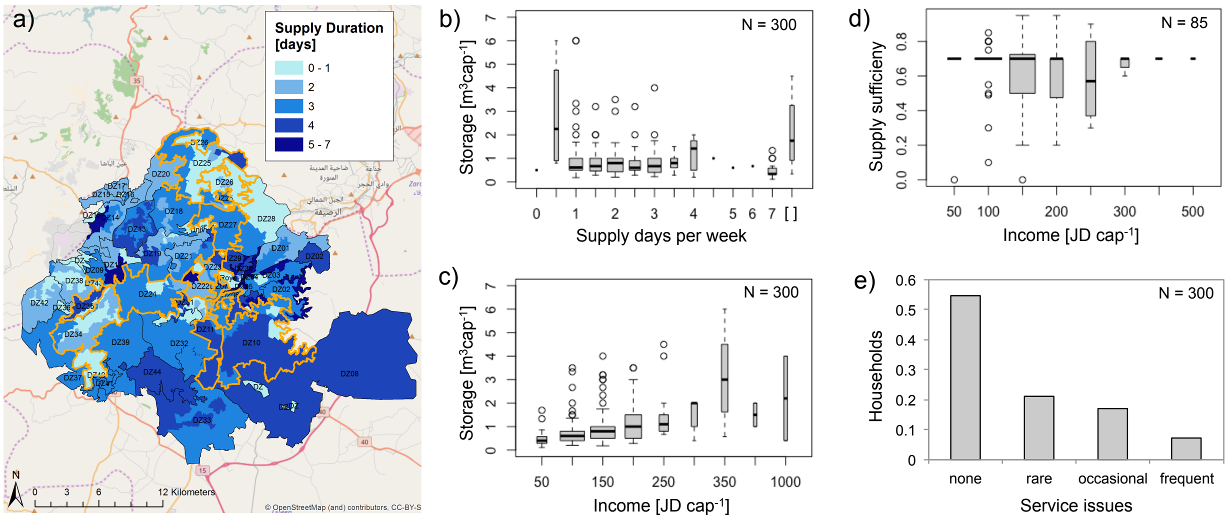

Figure 14a): Weekly duration of water delivery according to schedule and districts selected for household surveys (yellow lines); b) Correlation of household storage capacity with supply duration ([]=other); and c) with household income. Box width corresponds to group size (number of respondents per bin). d) Correlation of volumetric supply sufficiency from piped services and income. e) Frequency of perceived water issues. Map data (a) with courtesy of Miyahuna Jordan Water Company.

The (dis-)connect between citizens and the water resource system is empirically supported by a comparative assessment of perceived challenges to urban water supply security and sustainability. I interviewed 18 key stakeholders, who formed part of the "service providers" in Amman on what they saw as challenges to maintaining urban water supply in the long-term, and I asked the same set of 18 closed questions in the household survey. Details on the key stakeholder interviews including the interview questionnaire are provided in *Appendix 6*.

Results of the assessment of stakeholder perception alignment are presented in **Figure 15**. In the left panel, responses are compared between local and international key stakeholders. International donors and aid agencies significantly influence investment and planning decisions through financial and institutional support programs (Bonn, 2013), and I assume here that an alignment of perceived challenges and feasible solutions will make donor interventions more effective; a lack of which has been criticized in Amman's water sector (*KfW, pers. communication*; (Bonn, 2013)). While there is consensus on several issues, disagreement is significant regarding concerns about piped water quality (14% versus 40% for local and international stakeholders, respectively), the tanker water market (13% versus 50%), and water rationing (29% versus 60%). Some disagreement also exists on concerns about inequality of water supply (54% versus 80%), as well as water consumption for agricultural irrigation (62% versus 100%).

The right panel compares the responses of local key stakeholders and citizens. Perceptions were misaligned on the water price being too high (8% versus 63% agreed for local stakeholders and households, respectively), concerns about piped water quality (14% versus 77%), the tanker water market (13% versus 68%), water rationing (29% versus 69%), and potential solutions to the water challenges, i.e., the implementation of decentralized solutions such as greywater reuse (40% versus 92%). Some disagreement also existed regarding the "illegal" water market, inequality of supply, wasteful water use and the price/cost ratio. Citizens perceived the price for water services too high in relation to the services received, but seemed unaware of the cost for providing these services. While 86% of local water sector stakeholders stated water quality to be of no concern, 77% of surveyed households were of opposite opinion. A separate set of questions (Question#20 in *Appendix 5*) of the survey also revealed that of the 54% of households using piped water as a source of drinking water 79% filter water before drinking. Stated water quality problems were related to color, taste or smell (25%) and health problems (9%). While 80% of local key stakeholders regarded the tanker market as beneficial, and as a complementary source for areas not yet connected to the centralized piped system, or during repairs, 68% of households regarded the tanker water market as a challenge to water security and sustainability. Several factors stated by the surveyed household members could contribute to this perception: Tanker water is more costly than piped water, and the market and its prices are not regulated. Prices for tanker water paid by households ranged from JD 0.95-12.5 per m^3, while piped water is delivered at a tiered price of JD 0.7-1.6 per m^3 plus a fixed fee of JD 0.8-1.9. In addition, receiving tanker water requires time and effort, and although meant as a temporary subsidy, tanker water is a regular source of water for 14% of surveyed households. 92% of households saw potential in decentralized water management for addressing the urban water security challenge, which was considered beneficial by only 40% of water sector stakeholders. Although citizens and water sources are interceded by a complex urban SETS setup, the perception of water scarcity being a threat to future water security is closely aligned among citizens and local key stakeholders. The two groups' perceptions also closely aligned about the problem of water leakage.

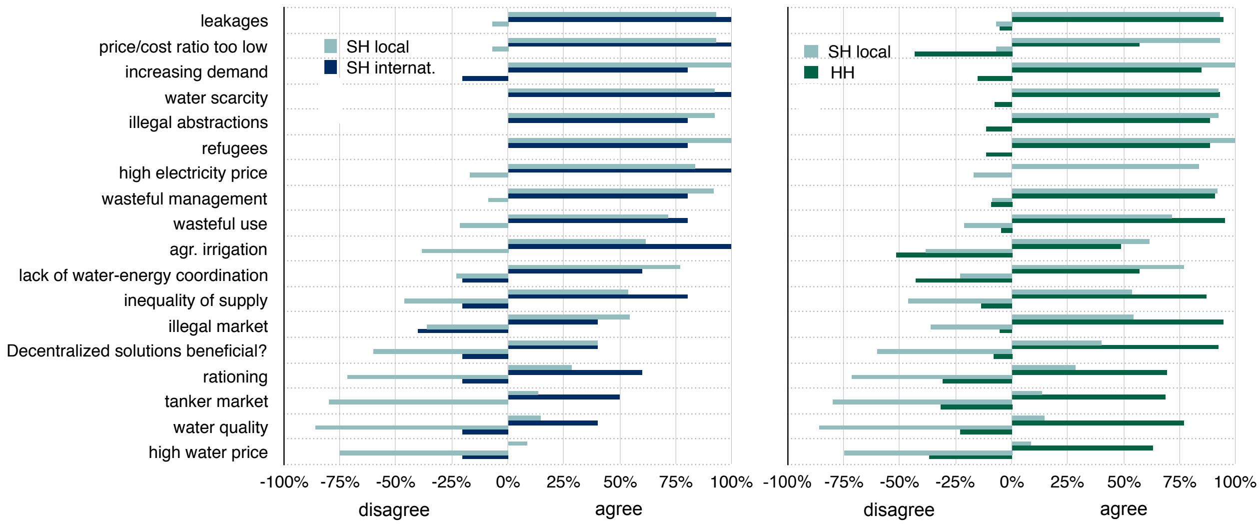

Figure 15: Alignment of stakeholder perceptions on challenges to the future security and reliability of urban water supply in Amman. Left: Comparison between local (SH local) and international (SH internat.) water sector stakeholders. Right panel compares local water stakeholder (SH local) perceptions and household (HH) perceptions.

Differences in perceptions indicate a lack of information from the service providers to the citizens and of feedback from the citizens to the service providers. In the open interview questions, key stakeholders stated financial and water scarcity as the two major threats to Amman's water sector. The interviews also revealed that urban managers perceived water rationing to increase citizen awareness of the water scarcity situation, and expected an initial increase in water consumption if rationing was discontinued. However, water quantity did not seem to be the main concern for citizens, who, when asked for the potential to save water in return for either financial compensation or increased reliability of services, 84% of citizens stated that they could save more than 10% of their average water use; 40% indicated a water-saving potential of 20-30%, and 13% said they could save 40% or more of average water consumption.

Interviews with international key stakeholders in Amman's water sector indicated a lack of feedback-loops, both between citizens and water service providers, as well as between various levels of hierarchy within the water governance sector. The lack of feedback-loops can lead to a divergence of perceptions between service providers and citizens, as indicated by the results shown in Fig. 15. Other sources suggest a disconnect between donors and resource providers (Bonn, 2013), which is supported to some degree by a misalignment of perceptions between international and local key stakeholders. Alignment of perceptions and the joint development of potential solutions are critical to a city's water supply sustainability, as it influences the decision space regarding urban water management options. The survey results reveal an openness on the part of the citizens to introduce more sustainable, decentralized water management options, and even for reducing water demand, in spite of current average water use from public services of only 92 lpcd. In contrast, urban water managers are currently not considering such options, and instead are investing into increasingly complex institutional and infrastructure setups, as well as costly water access infrastructure. However, while adjustment of water prices to recover costs is a political ambition, the misalignment of stakeholder perceptions, the disconnect between water providers and citizens, and the resulting lack of awareness make this ambition a socially challenging task.

3.4 Traps

[A version of this chapter will be submitted for review to a scientific journal.]

"[…] Modernity reflexively relies on increasing complexity to manage the very risks it creates and [...] the causes of catastrophes are often embedded in the very construction of social organization." (Centeno et al., 2015)

According to Cumming et al. (2014) urban and rural systems can end up in (poverty) traps, if ecosystems decline as a result of unsustainable resource management (rural poverty; urban overconsumption with unwillingness or inability to change). The poverty trap is "*a situation in which connectedness and resilience are low, and the potential for change is not realized*" (Carpenter & Brock, 2008; Gunderson & Holling, 2002). A poverty trap also appears in the model used to explain the emergence of inequality by Scheffer et al. (2017) (see **Box 1**): In a two-species version of the minimal model, multiplicative growth leads to a bimodal distribution, which is a consequence of the loss of "the middle class". The authors point out that, because multiplicity means *"absolute rates of exchange tend to nil as wealth goes to zero [...] low wealth is a "sticky" state"*. "Sticky" here means that getting out of it is extremely slow, which corresponds to a poverty trap. The bimodal character of the distribution indicates extreme inequality, where one group accumulates the majority of resources, while the other is left with near-to-nothing. Dadson et al. (2017) use a system dynamics model to show how a certain level of investment is needed to prevent economic growth being constrained by water security issues, and how the lack of investment into the avoidance of water-related risk can lead systems into a poverty trap.

In a model describing the relationship between adaptive capacity and traps Carpenter and Brock (2008) illustrate that a balanced exertion of adaptive control is needed to avoid two types of traps: poverty and rigidity. As systems focus resources and efforts to adapt to external forces and internal demands, systems become increasingly connected. Self-reinforcing institutions and reduced diversity as a result of management by command and control can lead these systems into a rigidity trap (Gunderson & Holling, 2002). Similarly, the race for singularity or collapse caused by accelerating innovation cycles proposed by Bettencourt et al. (2007) (see Box 1) can be seen as a rigidity trap.

In real systems, poverty traps are comparatively easily recognized. For urban water supply systems, we showed in *Appendix 2* (Krueger et al., n.d.) how the lack of and inability to marshal the necessary capitals leads to water services that are well below tolerable levels, and shocks quickly lead these systems into collapse. In the poverty trap, negative feedbacks prevail. **Figure 16a)** shows the causal loop leading into an urban water poverty trap. City-scale (public/ formal sector) characteristics are shown on the left, while citizen-scale characteristics (private/ informal) are on the right. The service deficit resulting from a weak public sector leads to a disconnect between citizens and the public/formal urban water sector, which is exacerbated by the lack of agency of citizens to voice their demands in the public realm. The emergence of informal water markets is accompanied by an unwillingness to pay for unsatisfactory public services, exacerbating the disconnect between citizens and the public/formal sector (Ashraf et al., 2016; Venkatachalam, 2015).

In rigidity traps, resources and efforts are focused to adapt to specific external forces and internal demands, which leads to highly connected, self-reinforcing, and inflexible systems (Carpenter & Brock, 2008). Sunk-cost and legacy effects of centralized, inflexible infrastructure impede adaptive management (Marlow et al., 2013). We proposed that rigidity traps are also a result of the development of excess water infrastructure, which is maintained at high financial cost, and that gradual loss of robustness bears the risk of losing resilience and shifting to an alternate state of low services, in spite of high capital availability. From the perspective of security and resilience, empirical proof of the rigidity trap is rare. Cumming et al. (2014) declare that evidence for cities suffering collapse from an urban trap is hard to deliver, except from archeological records, because current examples are successful at global upscaling. This is in line with our findings presented in Section 2.2 and *Appendix 2*, which show that security and resilience generally tend to co-evolve (Krueger et al., n.d.). However, sustainability adds an important dimension in understanding rigidity traps. Cumming et al. (2014) propose urban systems in traps to be characterized by unsustainable consumption, and that these traps tend to be resolved through upscaling, as they demonstrate for two examples (Beijing and Sweden). However, I suggest that global upscaling itself can be a trap, because given global urbanization and population growth scenarios, upscaling can only be a temporary solution (re: global change). In addition, upscaling involves the externalization of environmental (and social) costs, which means that the negative consequences of local trap avoidance impact regions elsewhere. Thus, while poverty traps are traps of local unsustainability, rigidity traps are traps of global unsustainability; and the latter can result in the former: For entire cities, if collapse occurs; or for parts of the population, if decline leads to inequality and fragmentation. Identifying the local manifestation of the rigidity trap is complicated by its global character. Strong robustness buffers shock impacts, and global upscaling currently prevents short-term failure, but if global resource limits were reached, collapse would percolate through a globally connected urban planet with catastrophic consequences. Such possibilities are discussed in the context of "global systemic risk" (Centeno et al., 2015). The mechanisms leading into rigidity are illustrated in **Fig. 16b**).

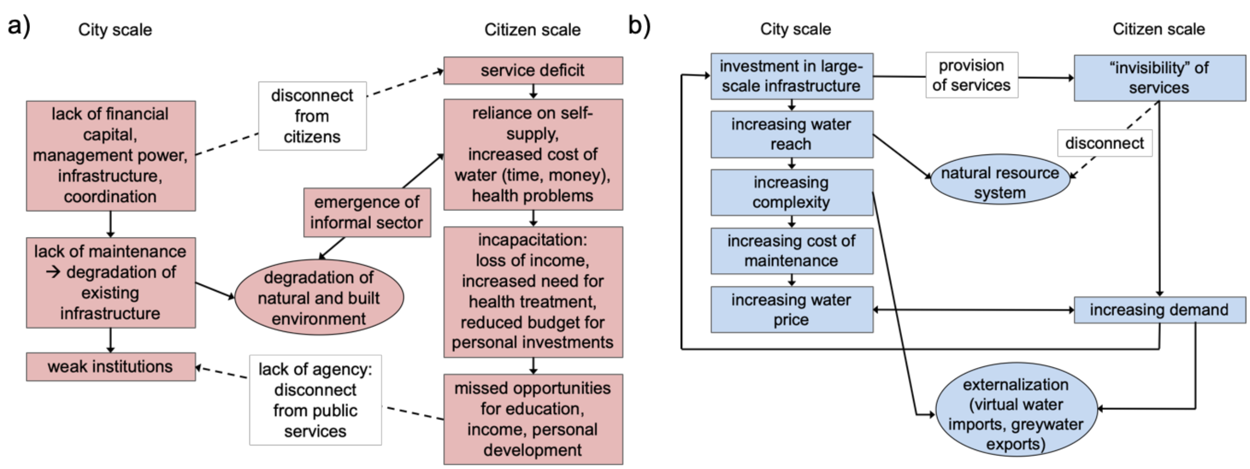

Figure 16: Causal loop diagrams: a) Urban water poverty trap; b) urban water rigidity trap.

In their model, Bettencourt et al. (2007) demonstrate the reliance of urban growth on increasing resource availability not only for increasing system size, but also for its maintenance. Their model takes the form:

$$\frac{dN(t)}{dt} = \frac{Y}{E}N(t)^{\beta} - \frac{R}{E}N(t) \qquad (3.5)$$

Where Y = units of available resources, R = units of resources required for maintenance, E = units of resources required for growth, N = city size (population). Depending on the values of β and R, for $\beta > 1$ and $N(0) < (R/Y)1/b$ the costs of maintenance dominate the system and the population collapses. This means that when the cost of maintenance exceeds the rate of growth, urban systems will collapse or will be caught in a poverty trap.

Infrastructure, such as dams and reservoirs for urban water supply are designed to deliver continuous water services, reduce the variability and increase the predictability of flow. However, the reduction of variability may introduce new vulnerabilities and exacerbate traps, as Carpenter et al. (2015) demonstrate. The authors analyze three natural resource systems and show how the control of short-term variance changes the frequency power-spectrum of variance. As a result of reduced short-term variance, systems become more prone to experiencing low-frequency, high-magnitude variance. The authors summarize the effects as follows:

1) Frequency shift: Reduced variance at high frequencies guarantees an increase at low frequencies, which can lead to the crossing of thresholds in the long-term.

2) Change of the safe operating space: Reduced short-term variance can change the boundaries of the safe-operating space, which can lead to the crossing of thresholds.

3) Missed information: Allowing variability reveals (non-linear?) system behavior under different conditions, and controlling variance is a lost opportunity to learn.

4) Lost resilience indicators: Higher variance near critical thresholds indicates loss of resilience, and control for variance means that change in resilience cannot be detected.

5) Lock-in of adaptive systems: Without disturbance, adaptive systems become unresponsive to change, which impairs the ability to adapt to gradual long-term change.

6) Impaired hardiness to shocks: Moderate stress promotes capacity to respond to shocks. Under controlled variance conditions, moderate stress is eliminated, which can lead to increased vulnerability to novel types of disturbances.

The six effects resulting from control of short-term variance impact different elements of the urban water system. Taking the five capitals of the CPA as guidance, variance is reduced to the convenience of the citizens, who can take critical infrastructure services for granted, and focus their attention on other activities ("invisibility of services" in Fig. 16b). Low variability of flow is also better for water infrastructure, as pressure variability and supply intermittence lead to higher degradation rates from changing flow pressure and the risk of intrusion of contaminants into water distribution pipes. So the six negative impacts concern the following: Water resources extracted from ecosystems are susceptible to frequency shifts and changes in the safe operating space; managers (management power, P) are affected by missed information and lost resilience indicators, which are important for sensing and anticipating changes; lock-in can affect the entire system: Assumption of stationary and stable conditions can lead to the implementation of rigid (inflexible) infrastructure and resource exploitation systems, financial and management unpreparedness for changing conditions, and community unpreparedness to deal with changes. "Impaired hardiness" could be translated to impaired preparedness: as discussed in Section 2.1 and in *Appendix 1*, community adaptation includes storage capacity at household level and in-house water treatment, as well as active social water networks, which is missing in systems with 100% services. Thus, the reduction of variance is a characteristic of, or can exacerbate the effects of the rigidity trap. This leads me to the proposition that: *Avoiding urban poverty traps requires local sustainable management; avoiding urban rigidity traps requires global sustainable management.*

4. Evolution of Urban Water Supply Systems

"... le génie inquiet et ambitieux des Européens ... impatient d'employer les nouveaux instruments de leur puissance..." Jean-Baptiste-Joseph Fourier (1809) (cited in (Said, 1978))

("... the restless and ambitious cast of the Europeans... impatiently striving to employ their new tools of power...")

Following city-scale assessments of urban water security, resilience and sustainability in Section 2, and intra-city patterns and processes determining system-scale resilience and vulnerability in Section 3, here, I return to city-scale investigations. This section covers two aspects: One is the transferability of the proposed frameworks, methods and concepts to global-scale analyses of urban water security, resilience and sustainability. The other is the long-term evolution of urban water supply systems, and how their trajectories can be managed over time. These investigations are guided by the following questions: 1) *How do the characteristics of urban water security, resilience and sustainability translate to the global scale?* 2) *How is the resilience of hydrological, social-ecological and coupled natural-human-engineered systems related? 3) How can we navigate the trajectories of urban water systems?*

Section 4.1 introduces the *Urban Budyko Landscape*, which is a translation of the hydrological Budyko framework to urban water systems using the CPA. A global typology of urban water systems is proposed. In Sections 4.2-4.4, the evolution of urban water supply systems is investigated using concepts drawn from social-ecological systems (SES) research. The four *components of resilience*, portrayed by Walker et al. (2004) using the metaphor of a stability landscape, are integrated with the CPA (Section 4.2). In Section 4.3 a schematic re-assessment of the historical trajectories of three case studies is produced within this new framework: Mexico City, Singapore and Ulaanbaatar, and a scenario is proposed for the latter, whose future evolution requires adaptive management in response to highly dynamic socio-economic and harsh environmental conditions. The *adaptive cycle* and *Panarchy* provide a different lens through which the evolution of urban water systems can be conceptualized, and connect the evolution of urban systems with environmental evolution processes, such as climate change (Section 4.4) opening another perspective for sustainability considerations.

4.1 Urban Budyko Landscape and Global Typology

[A version of this chapter will be submitted for review to a scientific journal.]

Common definitions of urban water security measure water supply as a fraction of water demand (Damkjaer & Taylor, 2017; Floerke et al., 2018; Jenerette & Larsen, 2006; McDonald, Green, et al., 2011; Padowski & Jawitz, 2012). I start here with such a volumetric input-output approach and use it to compare urban water supply systems with hydrological catchments using the *Budyko Framework.* Budyko (1974) introduced a simple, first-order relationship to characterize hydrological catchments by quantifying the partitioning of precipitation into evapotranspiration and runoff, and response to changes in climatic conditions (Greve & Gudmundsson, 2015; Roderick & Farquhar, 2011). Illustrations of the Budyko framework show catchments in a relationship of climatic conditions, where the evapotranspiration ratio, i.e., the ratio of actual evapotranspiration over precipitation in a catchment (E/P), is plotted against the aridity index, which is the ratio of potential evaporation over precipitation (E_p/P). The corresponding relationship is non-linear and constrained to physical limits, namely the atmospheric water demand ($E<E_p$) and the atmospheric water supply ($E<P$) (Greve & Gudmundsson, 2015). The framework has been used, among other things, to assess changes in catchment water balance as a function of climate change (Greve & Gudmundsson, 2015; Roderick & Farquhar, 2011; Zanardo et al., 2012).

Here, I propose that: *In analogy to the hydrological Budyko framework constrained by water demand and energy limits, urban water supply systems can be described and compared using the Urban Budyko Landscape with demand and service limits constraining their positions.* Following this proposition, I translate the hydrological framework to urban water supply system conditions, where the urban water supply ratio, corresponding to urban water supply over urban water resources S_W/W, replaces the evapotranspiration ratio (E/P), and the demand ratio (D_W/W) replaces the aridity index (E_p/P). W is defined as the per capita annual volume of water accessed for urban uses [$m^3cap^{-1}y^{-1}$], including naturally available, captured, reused, desalinated water, and S_W is the volume of water supplied [$m^3cap^{-1}y^{-1}$] and is limited either by the availability of W, leakage losses or by demand. Equivalently, D_W is per capita water demand [$m^3cap^{-1}y^{-1}$].

The resulting relationship of the Budyko curve as proposed by Fu (1981), and with the original climatic ratios replaced by the urban water supply and services ratios is described as follows:

$$\frac{S_W}{W} = 1 + \frac{D_W}{W} - \left(1 + \left(\frac{D_W}{W}\right)^a\right)^{\frac{1}{a}} \qquad (4.1)$$

The urban Budyko framework allows a comparison across cities, as to how water secure the different cities are in terms of water volumes accessed and supplied. In contrast to the discussion in Section 2, here, water security is measured only in terms of volumetric water availability at the city scale.

The CPA discussed in Section 2.1 and in *Appendix 1* introduces the multiple dimensions of water service security into the framework. This is done by replacing water resources (W) for water services. In the CPA water services are represented by the capital portfolio. Public water services result from four of the capitals (CP = [W,I,F,P]), while total services includes community adaptation (CP+A). In the systems dynamics model assessing urban water resilience (see Section 2.2 and *Appendix 2*), the three dimensions of the CPA (CP, RP and risk) are used as model input, and it produces fixed points. These represent the levels of water services S_{public} and S_{total} towards which the systems converge in the absence of shocks.

Figure 17 shows the relationship of 1) D_W/W and S_W/W (triangles), where D_W and S_W are volumetric water demand and supply, respectively; 2) D_{norm}/W and S_W/W (diamonds; see text below); 3) S_{total}/(CP+A) and S_{public}/(CP+A) representing the "system attractors" (squares) derived from the system dynamics model; and 4) D/(CP+A) and CP/(CP+A) (dots), where D=1 for full service security.

Lines represent different relationships of the Budyko curve as proposed by Fu (1981). The diagonal line represents the demand limit, i.e. data points on the diagonal represent cities, in which water supply meets volumetric demand. The further the data points are located from the demand limit, the larger the supply deficit. The demand limiting line intersects with the horizontal "supply limit", which follows from the fact that only the water in the system can be supplied. The size of the data points is proportional to the cities' water system "footprints", FP=1-MP. Melbourne, Singapore and Ulaanbaatar have the largest footprints, as they are unsustainably managed from a global perspective.

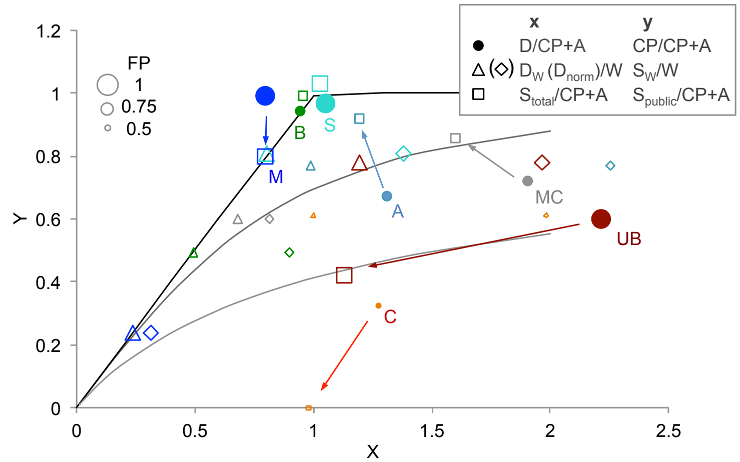

Figure 17: Urban Budyko Landscape. Dots are current system conditions (water supply services), squares are system attractors assuming elastic demand (from resilience analysis presented in Section 2.2), triangles are water ratios, and diamonds are normalized water ratios. Blue dot for Melbourne is outside the Budyko Landscape, as D = 1 is assumed. Melbourne's excess CP leads to a D/CP+A ratio <1. For Singapore, the system attractor (blue-green square) is >1, because CP+A<1, but S_{total}=1.

Using S_{total} in place of D assumes elastic demand, meaning that people adapt their demand to the total services they can attain. Normalized demand (D_{norm}) is used, because under constrained supply conditions, actual (or potential) demand is unknown. In the CPA assessment urban water security is based on a per capita availability of capitals. The per capita availability threshold for water security lies at 100 $m^3cap^{-1}y^{-1}$ or 274 lpcd (Krueger et al., 2019). The threshold is double the current water demand in many developed cities with modern water-saving devices installed in Northern Europe (Berlin, Hamburg, Amsterdam, Copenhagen) and Singapore, whose water demand lies between 45-50 $m^3cap^{-1}y^{-1}$. Between this lower demand level and the added 50% buffer, other developed cities in Australia, Japan, Europe and North America fall within the water security threshold (Melbourne, Brisbane, Toronto, Tokyo, Florence, Rome, Madrid, London), as well as all investigated cities in Africa, Asia, and South and Central America (that is, all but the US cities).

So, in contrast to the hydrological Budyko relationship, where for arid climates, E_P increases while P decreases, in cities with low W, D_W tends to be low, too, because people have adapted to low W (i.e., D_W is determined by average supply rather than by actual demand). However, in times of globalizing "urban lifestyles", I suggest to use a standard urban water demand that reflects assessments of water scarcity (Falkenmark et al., 1989; Liu et al., 2017; Vörösmarty et al., 2010).

The urban Budyko relationship (D_W/W versus S_W/W) is shown for 38 cities across the globe in Figure 18a), where the size of the circles corresponds to each country's global water footprint ($FP_{Wglobal} = 1\text{-}W_{global}$). Figure 18b) shows the location of cities with the standard (non-elastic) urban water demand (D_{norm}/W versus S_W/W). Fig. 18b) illustrates how cities located on the diagonal "sufficiency" line are shifted to the left, if their water use is greater than standard urban water demand, and shifted to the right, if their water use is below the standard. From this, global standards for water demand management could be derived: cities to the left of the diagonal should target a reduction of water demand (US cities, Athens), cities shifted further to the right have adapted their water demand (e.g., Cape Town, Windhoek, Conakry, Khartoum, Mbuji-Mayi, Berlin, Singapore), and urban managers should carefully analyze what the cost of this adaptation is for their citizens, potentially needing to consider an increase in their water supplies. Whether the standard should be 100 $m^3cap^{-1}y^{-1}$ is debatable and depends on available and affordable technology, given that modern cities with ample water resources are located to the right of the diagonal, such as Singapore and Berlin.

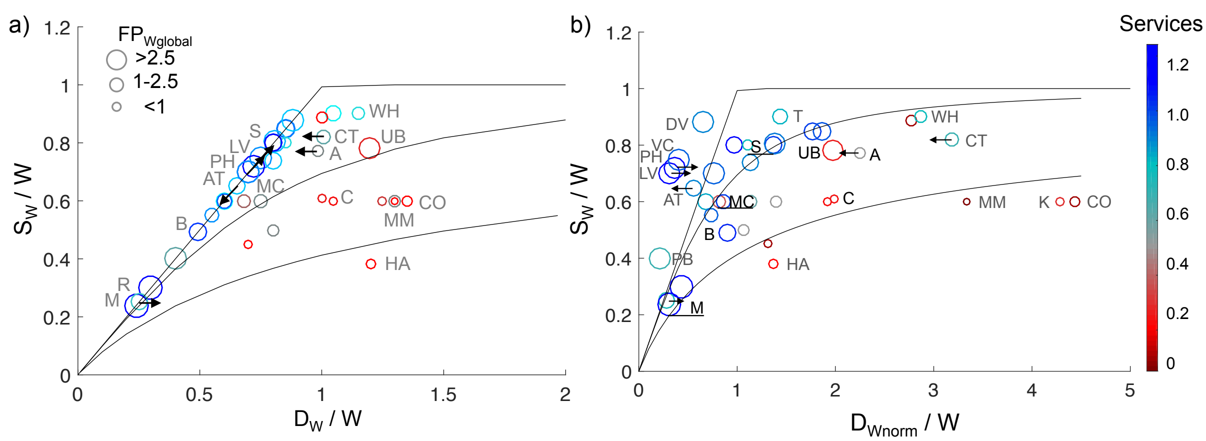

Figure 18: Urban Budyko Landscape showing 38 urban water supply systems, including seven cities described above and in Section 2.1. b) Equal (non-elastic) demand D_{Wnorm}= 100 $m^3cap^{-1}y^{-1}$.
Cities in the water secure and resilient regime (deep blue): Las Vegas=LV (NV, USA), Phoenix=PH (AR, USA), Melbourne=M (Australia), Athens=AT (Greece), Beijing (China), Florence (Italy), Madrid (Spain), Brisbane (Australia), Denver=DV (CO, USA), Toronto (Canada), Vancouver=VC (USA), Tokyo (Japan), Berlin=B (Germany), Amsterdam (Netherlands), Copenhagen (Denmark), Hamburg (Germany), Singapore=S;
Transition regime (light blue - grey): Cape Town=CT (South Africa), Windhoek=WH (Namibia), Tunis=T (Tunisia), Medellín (Colombia), Sao Paulo (Brazil), Amman=A (Jordan);
Transition regime due to decline: Rome=R (Italy), Pittsburgh=PB (PA, USA), London (United Kingdom), Mexico City=MC;
Insecure and non-resilient (red): Cairo (Egypt), Monrovia (Liberia), Mbuji-Mayi=MM (Democratic Republic of the Congo), Conakry=CO (Guinea), Kolkata (India), Lima (Peru), Hyderabad (India), Harare=HA (Zimbabwe), Khartoum=K (Sudan), Ulaanbaatar=UB (Mongolia), Chennai=C (India).

Colors in Fig. 18 indicate the estimated water security regime that the cities occupy. Examples of cities in the water-secure and resilient regime (blue) include some of those discussed above, i.e., Singapore, Berlin and Melbourne. Other examples include Amsterdam (Netherlands), which has long had to face challenges due to rising sea levels, the risk of flooding, and the need for reliable urban drainage (Disco, 2017). Adept water engineering created a sophisticated water system that emerged from the need to manage a precarious urban water situation located below sea level, and in a densely populated region that required managing compounded fresh water resources and relatively large amounts of wastewater (Brears, 2017). Windhoek (Namibia; “WH”) has turned to wastewater recycling for sustaining a growing population in spite of its arid geographic location (Lahnsteiner & Lempert, 2007; du Pisani, 2006). Despite low water availability, services are high, indicated by its location on the y-axis in Fig. 18.

Cities with few constraints regarding their access to water resources and financial capital are managing their water services with a supply-oriented strategy resulting in profligate water consumption. Examples include Las Vegas (Nevada, USA), Phoenix (Arizona, USA), and Rome (Italy). More recently, a combination of growing demand and extended drought periods, or incrementally increasing competition for resources indicate that previously bountiful water resources could become scarcer in the near future, bringing to the table the question of sustainability of such supply-oriented approaches (Barnett & O’Neill, 2010; DeBuys, 2013; Giuffrida & Taylor, 2017; Goldenberg, 2012; Horowitz, 2017; Shannon, 2018). This is indicated by arrows, which point in the current direction of urban water trajectories. Estimations are based on reported declines and plans for addressing water security challenges as cited in *Appendix 7*. In Fig. 18a) arrows pointing upward along the diagonal from the lower left, water-abundant regime indicate that the artificially created "super abundance" for Las Vegas ("LV"), and Phoenix ("PH") may decrease over the coming years. The two cities located in the arid southwest of the United States (US) have developed large-scale water storage and/or transfer schemes taking water from the central US states. Water demand in these cities is around 600 lpcd, showing no demand management in spite of the cities' arid locations. Recurring droughts in the past years have threatened the two cities of "running dry". Fig. 18b) shows that for these cities, potential lies in managing for water demand, rather than increasing water availability. For Athens (Greece; "AT") the arrow is pointing in the opposite direction. Athens has one of the most ancient aqueduct systems, which has been repeatedly expanded over the centuries, and, although water availability is high, urban managers are proposing yet another water import expansion, which would increase the ratio of demand over water resources until demand follows suit (Stergiouli & Hadjibiros, 2012). This indicates that 1) demand management is needed and 2) significant fractions of water available to the city is likely lost through leaking pipes. Rome (Italy, "R"), though water-abundant, is in the decline regime, having leakage rates as high as 45%, and droughts have led water managers to threaten having to resume to water rationing, as well as keeping pressure high to exploit remote water resources (Giuffrida & Taylor, 2017). While Cape Town (South Africa; "CT") has been living through a severe drought threatening with a "day zero" scenario for cutting off piped water supply (Welch, 2018), urban managers are in the process of implementing new water supply schemes, which will move the city further into the water abundant regime (arrow pointing left). Amman (Jordan; "A") is aiming towards higher water security with a desalination and water transfer project from the Red Sea to the country's urban areas in the making (top-most data point, arrow pointing left) (Coyne et Bellier et al., 2012).

Based on the assessments above, Figure 19 shows a map of the 38 cities, where the size of the data points corresponds to average per capita water use and the color filling represents the cities' current water security and resilience regime. Water secure but rigid water systems that emerged from a "risk management" paradigm predominate in North America, Australia and China. Their systems are fully centralized, based on inflexible infrastructure that has to be maintained at high cost. Urban water demand is highest in the US, where domestic water use reaches upto 600 lpcd, resulting from yard irrigation, abundance of swimming pools, and use of water-intensive household appliances.

Lack of investment and maintenance of old infrastructure is showing signs of degradation in several cities, such as in Mexico City, London and Rome. Recurring droughts, lack of demand management (low levels of water metering) and neglected water distribution networks have degraded London's water service system. Pittsburgh (PA) experienced pollution of drinking water with lead, has been threatened by radioactive contamination resulting from the fracking industry, and weak institutional response has put customers at severe health risk. Thus, while infrastructure and the institutional setting are adequate in terms of securing and distributing sufficient volumes of water to meet demand, the lack of water quality management leads to declining water services in the face of increasing pollution pressures.

Water supply and sanitation problems are among the most prevalent in urban slum areas, home to around a billion people worldwide (UN-Habitat, 2016a). Water insecurity of slum dwellers affects 20-60 % of citizens in many African, South and Central Asian, and South American cities (UN-Habitat, 2016a): Urban managers are struggling to provide their citizens with adequate water services due to a lack of capitals, keeping large parts of the urban population trapped in water poverty, such as in Chennai, Hyderabad, Bangalore (India), Mexico City, and Accra (Ghana) (Bell & Hofmann, 2017; Eakin et al., 2016; Harris et al., 2017; Potter et al., 2010; Srinivasan et al., 2010b). High water demand in Lima (Peru), indicates that the apparent urban water abundance comes with high inequality among urban residents, most of whom are without access to water delivery (Hommes & Boelens, 2017). Several cities have been making significant progress towards water security, and are in a transitional state. Among these, Windhoek is the only one that has embraced water recycling as a major strategy to water security (Lahnsteiner & Lempert, 2007), while all other cities shown here are focusing on conventional, centralized and rigid infrastructure.

Color outlines indicate the cities' global water sustainability regime ($M_{W global}$). The largest water consumers in the US are also globally highly unsustainable due to their large ecological and external water footprint (low $M_{W global}$). Singapore, and Ulaanbaatar, and the two Australian cities are also highly unsustainable. The European cities, as well as Beijing, Tokyo and Windhoek have slightly higher levels of $M_{W global}$, while the remaining cities have intermediate (>0.2-0.4) and intermediate to high (>0.4) levels of $M_{W global}$. As discussed in Section 2, while the patterns for water security and resilience are somewhat expected, sustainability is highly heterogeneous.

Several cities have started investing into locally more sustainable water management strategies (e.g., Singapore, Berlin, Melbourne, Amsterdam, Windhoek; local sustainability not shown in the map), such as the integration of water and energy systems. Tokyo is a world leader in reducing leakage from their water distribution networks, as well as in precise water management. But their system, too, is inflexible and citizens have high water demand. No city appears in the balanced regime, in which security, resilience and (local and global) sustainability are balanced, which would result in green color filling and green outlines.

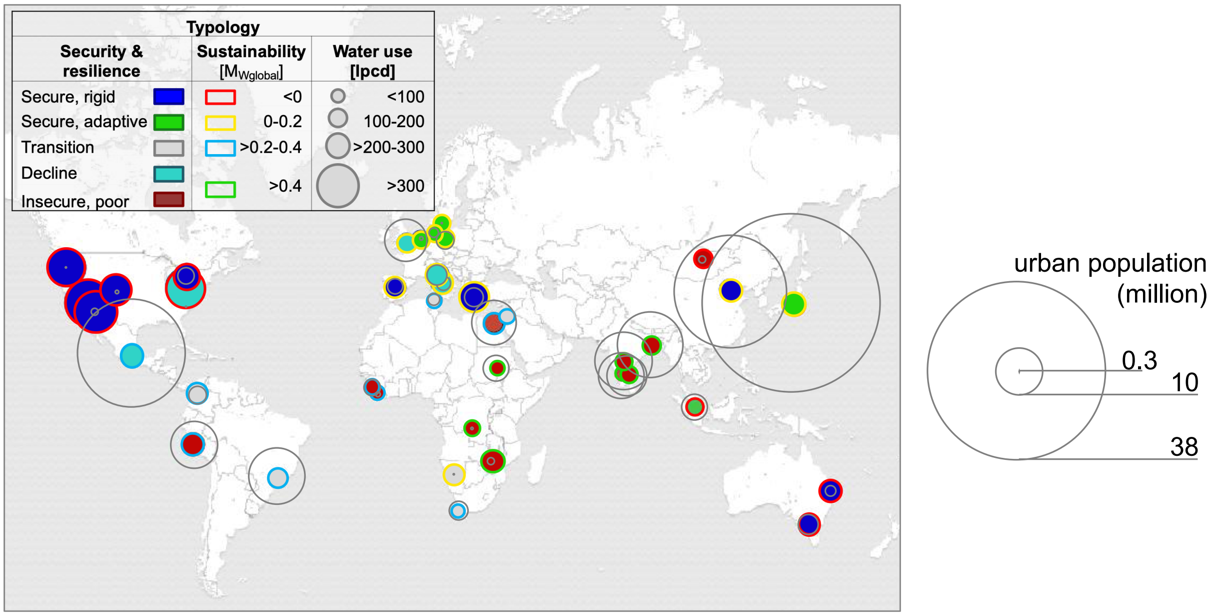

Figure 19: Map of global urban water types.

4.2 Managing Urban Water System Evolution

[A version of this chapter will be submitted for review to a scientific journal.]

The discussion so far has covered the assessment of system functions, dynamic behavior, and the direction of the current trajectory based on an assessment of sustainable management. The global overview of urban water archetypes presented above raises the question how these cities evolved to their current status? How does the management of security, resilience, sustainability and risk change the trajectory of urban water supply systems?

Walker et al. (2004) use the metaphor of a stability landscape to describe the four components of resilience: The width (latitude, L) and depth (resistance, R) of the basins of attraction describe the shape of the stability landscape. The location of a system within the landscape is described by the distance from the nearest boundary of its current basin of attraction (precariousness, P). The fourth component, panarchy, relates to cross-scale and cross-sectorial effects that can influence the system. The authors refer to the adaptability of the system as the corresponding actions that can be taken to control the system trajectory. Control of trajectory refers to actions influencing a system's precariousness, changing the topology of the landscape refers to actions that increase the width (latitude) or depth (resistance) of the basin, and changing processes in response to dynamics at other scales and sectors refers to control of panarchy. This is illustrated in **Figure 20a)**.

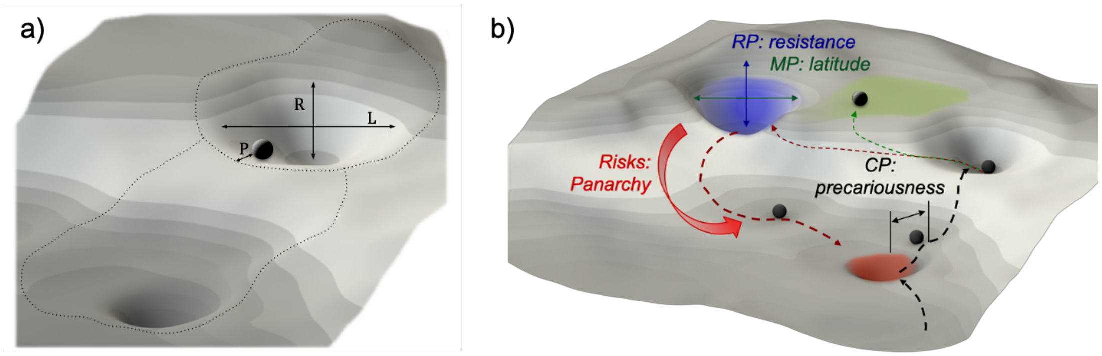

Figure 20: Stability landscape with basins of attraction. Black dot = current position of the system and components of resilience. **a)** System's distance from the nearest boundary of the basin: precariousness (P), width of the basin: latitude (L), and depth of the basin: resistance (R). Adapted from: Walker et al. (2004). **b)** Integration of the stability landscape with the CPA. Security and resilience regimes - red: poverty trap; grey: transition; green: adaptive regime; blue: rigidity trap. Four components of resilience managed through four dimensions of the CPA: CP, RP, MP, cross-scale and -sectoral risks). Graphics: JF Krueger

Fig. 20b) integrates the components of the stability landscape and the Capital Portfolio Approach (CPA). The dashed lines mark possible trajectories of CNHES: Starting from the area of the poverty trap (red), adding CP reduces system precariousness and moves the system through the transition regime (grey). In the adaptive regime (green area), latitude (width) can be gained through sustainable management (MP). Resistance is gained by adding robustness (RP), which is emphasized here in the deep valley of the rigidity trap (blue). Such a trajectory marks the "Business As Usual" (BAU), and the system starts with low CP at the bottom right corner to high CP at the top left within the area of the rigidity regime. The red dashed trajectory marks the system moving out of the rigidity trap, decreasing RP and CP through degradation and decline. Managing unforeseen impacts that act across scales (or sectors) can be achieved through careful sensing and monitoring of the system environment, and by managing risks and cross-sectorial aspects (panarchy, red arrow).

These trajectories are also marked as red and green paths in **Figure 21**. In the Urban Budyko Landscape (Fig. 21a), cities start out in the bottom left-hand corner, as demand and services are ≈ 0, and move to the right as cities grow and demand for water resources increases accordingly. When demand exceeds services (x-axis>1) urban managers are pressured to provide water services through the construction of infrastructure and the implementation of institutional structures supporting their management. Once services and water resources meet demand (trajectory reaches the diagonal line), cities tend to develop excess water availability ("W"; e.g., storage, water transfers, desalination plants) in order to provide water for varying demand ("supply-oriented management regime") and to have buffer for naturally occurring variability (e.g., major drought cycles). This moves cities down along the diagonal line towards the bottom left of the Urban Budyko Landscape. Once a city is unable to maintain the large, inflexible and excessively built infrastructure, they risk sliding into decline towards the end-point of the dashed trajectory line. Alternatively, cities can incorporate natural variability of water availability into their management by carefully managing available resources (e.g. through water recycling, demand management, etc.), and maintaining flexibility in the water management system, which is illustrated by the green trajectory. The red trajectory illustrates the path into a poverty trap, where demand increase is initially responded to by developing services, but the joint development of infrastructure and institutions is insufficient for keeping pace with continued demand increase and incremental degradation of infrastructure and institutions.

Fig. 21b) presents the two trajectories (BAU and Adaptive Management) in the resilience landscape introduced in Section 2.2. The co-evolution of CP and RP lead to increasing levels of services, which, if sustainably managed, move into the sufficiency regime, or else move through the rigidity regime and end up declining, moving back down towards lower levels of services. Colors in Fig. 21 correspond to the colors in Fig. 20b), marking the different regimes ("attractors").

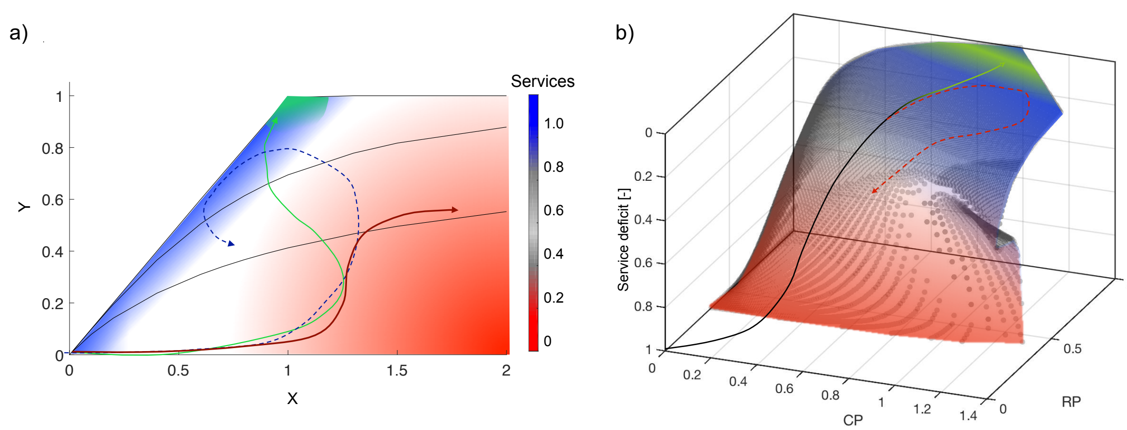

Figure 21: System trajectories: **a)** Urban Budyko Landscape. Dashed: "Business As Usual (BAU) trajectory"; The BAU trajectory moves from the poverty regime (red) through the transition regime into the rigidity regime (blue). Solid green: "Adaptive Management trajectory". Red: Trajectory leading into a poverty trap. X and Y-axes are ratios of volumetric supply or water services over water resources or capitals (adapted from (Krueger et al., n.d.)); **b)** Resilience landscape with same water system trajectories as in a).

4.3 Trajectories

[A version of this chapter will be submitted for review to a scientific journal.]

The long-term trajectories of Mexico City (Tellman et al., 2018), Singapore (Public Utilities Board, 2013), and Ulaanbaatar are examined here using the framework presented above, combining the three cities' current CPA, the Urban Budyko Framework, and the urban resilience landscape with historical recounts to understand how the cities evolved over the centuries. The purpose is to explore the conceptual framework for understanding urban water system evolution and how to quantify it based on knowledge about current system conditions as presented in Section 2 (Krueger et al., n.d., 2019), rather than to present data for determining the exact state of the systems at a certain point in time for the entire trajectories. **Figures 22** and **23**, summarize the cities' journeys and schematically describe their water system trajectories with a few selected historical milestones marking turning points and periods of prolonged development or decline.

Mexico City: Tellman et al. (2018), describe the evolution of Mexico City over the past seven centuries: Founded by the military leaders of the Aztecs in 1325, the city, then Tenochtitlán, was first built as a citadel on an island in the middle of a saline lake with limited access to clean drinking water. To provide food and water for the growing population, they constructed dikes and sluices to maintain a wetland agriculture system, as well as aqueducts (first recorded in 1381), and violently dominated surrounding populations to secure their access to water and other resources. The trajectory in the Urban Budyko Landscape shown in Fig. 22a) starts in the bottom left-hand corner: growth of the population increases the demand over availability ratio, moving from left to right along the x-axis. Investment into dams, dikes and aqueducts, as well as institutions to manage this infrastructure meant creation of CP, moving the system upwards on the y-axis. The Aztecs managed the natural cycles of water abundance and scarcity with knowledge of the local environment. The system was able to buffer natural variability, had a relatively small size and the locally adapted design meant that the system had robustness (RP) and was sustainably managed (latitude/MP). These developments moved the system into the transition regime.

Transition: The Spanish *conquistadores*, who arrived in 1521, destroyed Tenochtitlán (loss of CP) and decided to build their new capital on its ruins (gain of CP). They followed the strategy of their predecessors of subjugating peoples in the surrounding areas for their access to water resources. However, the new settlers failed to maintain the Aztec's water management system and deforested the land that acted as a buffer to the natural hydrological variability (loss of RP and MP). As a result, the settlement became vulnerable to flooding and droughts (increased risk/panarchy); runoff increased, eroded sediments filled lakes and raised lake levels, and groundwater infiltration decreased. Soon they were faced with devastating floods in 1555. Another major flood occurred between 1629-1634, which killed 30,000 people and caused another 50,000 to abandon the city (loss of CP). This dynamic period of repeated rise and collapse lasted until the mid-19th century, and is marked in Fig. 22a-c) by a chaotic section of the system's path moving through the landscapes. Recurring floods and devastation caused the new Spanish leaders to repeatedly consider moving the city to more favorable surroundings, but each time the decision was to stay and conquer nature, which, until this day is proving as a mal-adaptive strategy.

Rigidity: Continued population growth made imported water resources insufficient, and starting in 1870, Mexico City's managers promoted local groundwater as the primary source of water. During the same period, urban managers constructed the Gran Canal, which was to relieve the city of the recurring floods from excess stormwater as well as wastewater. This period (1870-1900) was marked by considerable increase in CP, moving it closer to the demand-limiting line in Fig. 22a), the water-secure area (blue) in Fig. 22b), and towards the "valley" of the rigidity trap in Fig. 22c). However, the rigidly built infrastructure became increasingly vulnerable to external shocks and disturbances, such as flooding, drought, and earthquakes (panarchy).

Decline: The latest phase, starting around 1920 and continuing to this day, marks the decline of the metropolis, which today counts around 23 million inhabitants. Continued demand growth urged the urban managers to construct two large-scale water import systems: Lerma in 1970 and Cutzamala in 1982, which was followed by further urbanization and population growth. These water import projects have put the city into socio-political conflict with neighboring populations, who are defending their land and waters against the urban claims (Watts, 2015). The city's focus on the construction of large-scale, inflexible infrastructure, ignorance of the natural and social environment, as well as the sole focus on supply-side management drove it into a rigidity trap, which proved unsustainable (gain of CP, loss of MP). Urban groundwater pumping was soon followed by the first recording of land subsidence in 1920, which reached 18 cm per year from 1930-1960 (loss of CP and RP) and is still a major problem today. Although the decision for groundwater pumping was later temporarily reversed, and attempts were introduced to manage demand, the decline of the city's water system was uncontainable. Prioritization of investments into growth and access of additional resources over the maintenance of existing infrastructure has resulted in the same amount of water imported being lost through leakage in the decrepit distribution network. Fig. 22a) illustrates that, while water availability has been increasing, seen by following the dashed line towards the triangle close to the diagonal line, water services have moved increasingly further from water security as indicated by the solid line towards the dot. Today, in spite of water abundance at the city level, water supply is rationed, and only 10% of wastewater is treated (Tortajada & Castelan, 2003). Land subsidence throughout the basin is crushing the underground pipe network, leading to large leakage losses, and increasing risk of flooding (Kimmelman, 2017). 20% of the population are without connection to the central supply system, and for them attaining water is costly (upto 20% of household income) and involves bribing and violence. Acute diarrheal diseases caused by the lack of or decrepit infrastructure pose a significant challenge to people's health and livelihoods (Lankao & Parsons, 2010).

Singapore: Modern Singapore's water trajectory starts from its foundation in 1819 (population approx. 1000) until today (population approx. 5.5 million), as presented in **Figure 22d-f)**. Singapore was initially massively deforested, as the island was intended to become a major trading post (and later a British naval base), and by 1886 only 10% of the original forest remained (low MP). Within that time, the population had risen from around 1,000 to around 80,000 (Abshire, 2011), which is illustrated by the trajectory moving towards the right along the x-axis in Fig. 22d). Pressure increased to supply the growing population with water, and the first reservoir and distribution system was operational in 1877; 25 years after its first planning. Additional reservoirs were constructed in 1913 and 1949 (increase of CP). The remaining forests in the catchment areas have since been protected for water production (maintaining MP). Water imports started in 1927, after the first treaty was signed with Malaysia. The importing pipeline was unintentionally destroyed by retreating British troops in 1942, and between 5,000-25,000 Chinese citizens were killed during Japanese rule (1942-1945; dropping levels of CP). Singapore became an internally self-governed state within the Commonwealth of Nations in 1959, the year in which the first Prime Minister, Lee Kuan Yew, was elected, who promoted the development of Singapore's water sector (Abshire, 2011).

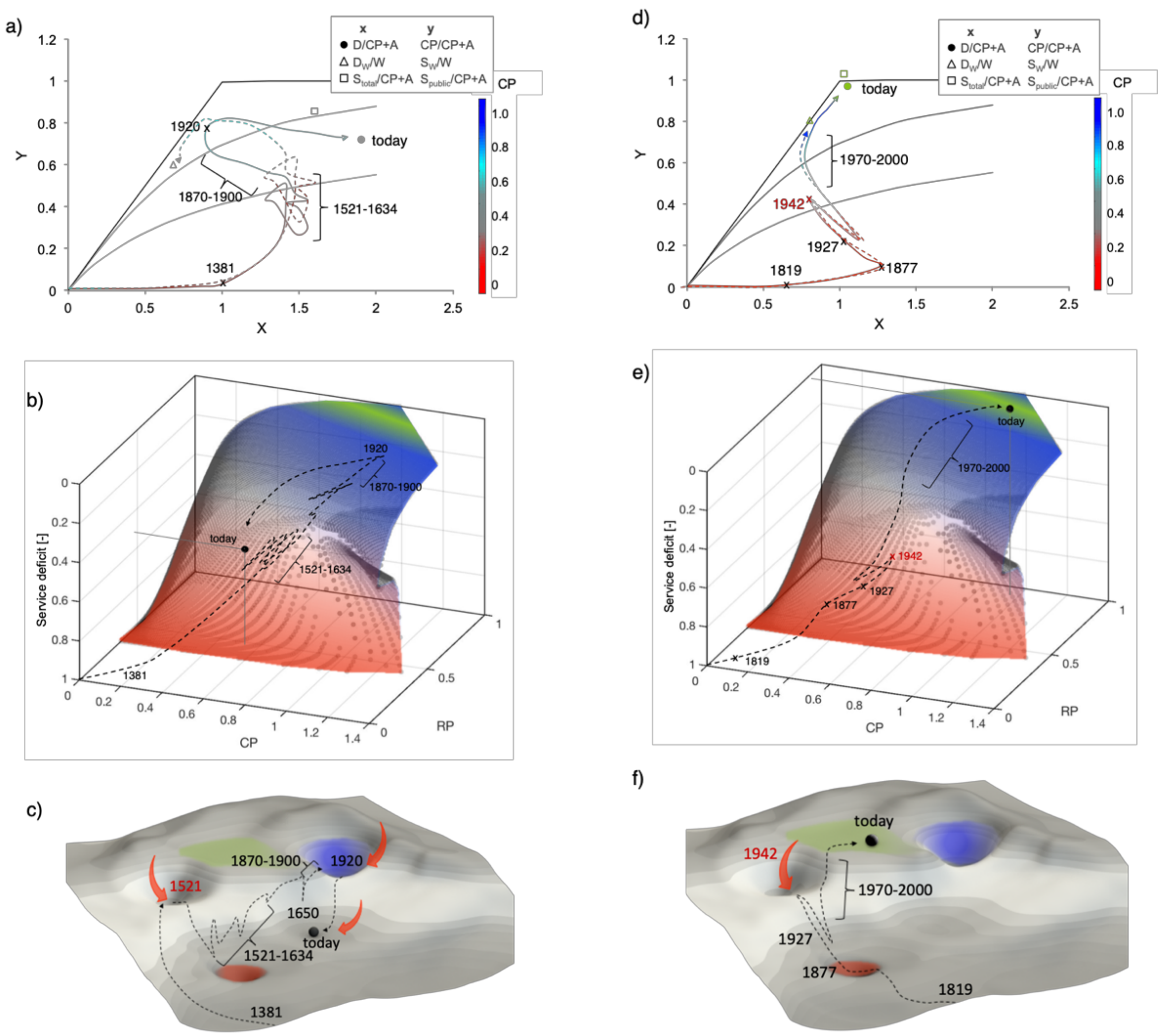

Figure 22: Schematic historical trajectories of urban water supply security and resilience. Left panels: Mexico City; right: Singapore. **a, d)** Urban Budyko Landscape: ratios of D/CP+A and CP/CP+A (solid line), and for D_W/W and S_W/W (dashed); **b,e)** resilience landscape (adapted from (Krueger et al., n.d.)); **c,f)** stability landscape following (Walker et al., 2004; graphics credit to: JF Krueger).

<u>Mexico City's historical milestones</u>: **1381:** first water imports from Chapultepec springs, followed by further water imports; **1521-1634:** repeated floods and devastation, introduction of more aqueducts; **1870-1900**: industrial development, groundwater exploitation, expansion of water reach into indigenous land, reconstruction of destroyed aqueducts, construction of Gran Canal**; 1920**: first land subsidence reported**; 1930-today**: decline - exponential population and water demand growth, degrading infrastructure and institutions, major water import projects (Lerma: 1970; Cutzamala: 1982). Dashed line in 22a): First reported land subsidence in 1920 followed by construction of major water import projects leads trajectory down the demand limiting diagonal line. This implies that in spite of additional water imports, the level of services was only maintained through increased water availability (solid line moves approx. horizontally to right).

<u>Singapore</u>: **1819**: Foundation of modern Singapore; **1877**: First reservoir and distribution network in place (population: ~80,000); **1927**: First water imports from Johor (Malaysia); **1942**: Destruction of water import pipeline; **1963**: Foundation of Public Utility Board; **1970-1990**: Construction of estuarine reservoirs and water harvesting within urban catchment; **2000-today**: Implementation of desalination and water reclamation plants, "Four taps" in place.

Created in 1963, the Public Utility Board (PUB) has been responsible for establishing piped household water connections and sanitary sewer systems. The vision of making Singapore a "garden city" was proclaimed in 1967 with the aim of limiting the loss of the remaining natural flora and fauna, and today 10% of the country's area is set aside for parks and nature reserves (maintaining local MP). Land reclamation projects have relieved the pressure to urbanize the remaining natural areas by increasing Singapore's land area by 23% from 582 km^2 in 1960 to 722 km^2 today. The first Water Master Plan was conceived in 1972 (institutional development adding to CP). During the following decade several (estuarine) reservoirs were created for additional water resources, and in 1986, the first urban rainwater harvesting project was introduced (increasing CP and MP). By the 1990's half of the country served as a water catchment for the city's needs, which was up to 66% by 2013 (Khoo, 2009; Public Utilities Board, 2013).

Today, Singapore is regarded as one of the world's water innovation hubs. Water reclamation using membrane technology was introduced in the 2000's, desalination in 2005, and today all used water is treated and reused either in industrial processes, or to top up reservoirs during dry years. This NEWater makes up 30% of water demand, planned to cover 55% in the future (high MP). To facilitate coordination for an integrated management, water supply, sewerage, and drainage and reuse management were integrated in a reconstituted PUB under the Ministry of Environment (increasing MP) in 2001. After negotiations with Malaysia about a new agreement for water imports beyond 2061 failed in 2003, Singapore's decision-makers aimed to make the state water-autonomous before 2061 (which will require an increase in CP and RP).

Due to the emphasis on closed water cycles, the integrated nature of its water, sewerage, and stormwater management, the transparency of management, and the combination of supply- and demand-oriented management makes Singapore's approach a locally sustainable one (Joo & Heng, 2017; Luan, 2010; Ziegler et al., 2014). This trajectory is illustrated in Fig. 22d-f). Fig. 23d) demonstrates that for systems with carefully managed water resources the trajectories of D_W/W and S_W/W, and of D/CP+A and CP/CP+A coincide. However, while green colors mark the location of Singapore (local sustainability), the city practices globally unsustainable management. A reasonably large shock could push the city from the "adaptive plateau" into decline. This can result from rising sea levels due to climate change (to which Singapore itself is contributing with a large global footprint), or other factors such as a global economic crisis (Singapore has significant international financial dependence as pointed out in Section 2.3). This would be an effect of panarchy due to the lack of global sustainability (see Section 4.4). In addition, Singapore has not yet moved towards integration of the water, energy, and solid waste sectors. The future evolution of Singapore's water system will be determined by the management choices to changing external conditions.

Ulaanbaatar was founded in its current location in 1778, when moving the formerly nomadic yurt monastery became less convenient as it grew beyond approximately 10,000 monks. Throughout its history, Ulaanbaatar served as a trading post between Russia and China, and by 1910, its population had grown to around 60,000. After the Second World War, new apartment blocks replaced the old Ger districts. Urban planning began in the 1950's, with much of the city today being the result of construction during 1960-1985 (increase of CP). Beginning in 1990, after the end of the socialist regime over Mongolia, many of the country's steppe nomads began moving to the cities, as government support and regulation of the nomadic lifestyle came to an end (Diener & Hagen, 2013; Fan et al., 2016). This led to a steep decline in relative water and service availability due to the increase in demand, as can be seen from the trajectory after this date in **Figure 23a-c**). Recent construction of infrastructure began as economic and urban growth took off in the early 2000's, when a short-lived economic boom set in after the turn to a market society (Diener & Hagen, 2013; Fan et al., 2016), switching the trajectory back towards increasing services and a lower demand over availability ratio in Fig. 23. However, this growth has reversed (loss of CP due to demand growth and lack of RP), and the economy has stagnated at low levels, since the economic boom was only driven externally from foreign investment into the extraction of the country's mineral resources (low MP). Reliance on a narrow economic sector, whole-sale of resources without the introduction and enforcement of environmental regulation to protect water and other ecosystems, has threatened the health and livelihoods of people living in or downstream of industrialized or mining areas (Karthe et al., 2015). While the construction of upper-class apartment complexes continues to serve a wealthy and international upper class, inequality is on the rise. The prospect of moving from make-shift housings, which lack basic infrastructure into more modern urban dwellings remains unattainable for the vast majority of the 60% urban dwellers, who live in Ger districts (equivalent to slum areas) (Engel, 2015; Fan et al., 2016). Meanwhile, existing infrastructure dating back to socialist rule is long past peak performance, and desperately needs modernization. Rural-urban migration continues, as nomadic life is becoming increasingly trying. This is a result of climate change, land degradation due to the lack of regulation of stock numbers, and inadequate support structures for small-scale nomadic herders. The city roughly has enough water resources to meet demand (shown by the triangle in Fig. 23a), but services are so low that its current status (dot) is to the far right of the sufficiency line. This indicates that management efforts should be targeted at improving services, rather than accessing additional resources.

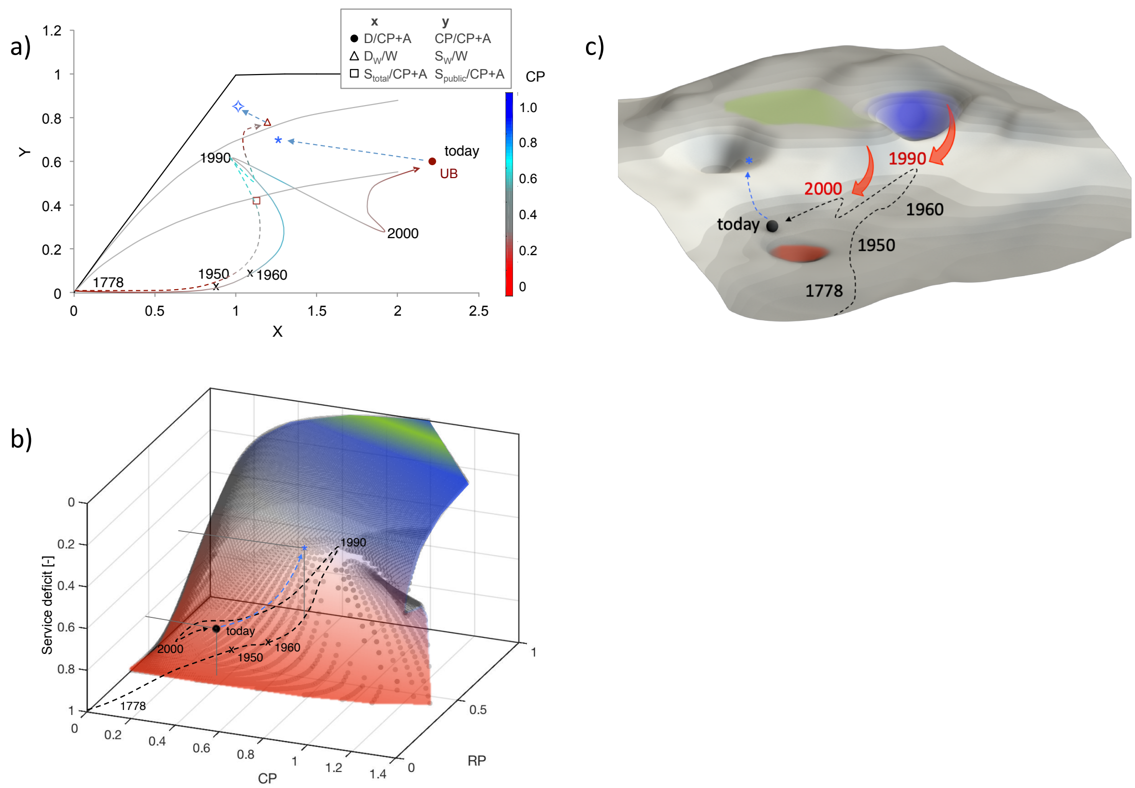

Figure 23: Historical trajectory of Ulaanbaatar's water supply system (1778-today) and future scenario (*). Historical milestones: **1778**: Foundation of Ulaanbaatar at its current location; **1950**: First urban planning; **1960's-1985**: Construction of urban water infrastructure under Soviet rule; **1990-2000's**: End of Soviet rule: decline of existing infrastructure and institutions; **2000's-today**: urban population growth, increasing water demand, construction meets only increasing urbanization (level services); **Today- *:** Strengthened management and smart investment scenario.

4.3.1 Managing Ulaanbaatar's Future Water Trajectory

Trapped in a situation of declining economic dynamics, population growth, and a desperate need for investment into infrastructure, Ulaanbaatar's managers are challenged to make sustainable decisions for laying the foundations of the city's future water trajectory. However, changes in the system's CP and RP can, if adequately managed, guide the system onto a more sustainable trajectory. Below I create a scenario that moves the city's water system into a more robust transition regime by 2030, marked by an * in Fig. 23. **Table 1** shows values for the current quantification of the city's CPA, as well as for its future scenario (*). For details of the method see *Appendix 1*.

In the proposed scenario, CP, RP and MP are increased as follows: Water resource availability increase from W=0.51 to 0.62 (51 versus 62 m^3 per capita and year, respectively) could be achieved through the construction of a few small-scale dams and the protection of forests in the river's upstream area (increase in M_W). Water resource robustness R_W will thereby be increased, as the city's source diversity is elevated, and the use-to-resource ratio is reduced. To further improve the robustness of water resources, water quality measures including source control and the polluter pays principle need to be implemented. The status of infrastructure is improved by increasing household connection rates from 41 to 55% of the population for water supply and sanitation, which could be achieved with the help of donor organizations. This could be done by improving inter-sector coordination working towards integrated water, waste and energy management, as well as opening up the path towards water recycling (increasing RP through improved MP). The increase in piped water connection rate increases the financial budget (F) by slightly reducing the need for infrastructure investment, and robustness of financial capital (R_F) is increased by improving cost recovery. Management power (P) is strengthened through improved institutional efficiency by ensuring inter-sector coordination, and through bettering accountability by involving the public in water governance, which can be achieved through public information and participation events, and by incentivizing the public to become water stewards for improved water protection and water saving (increased R_P through M_P). Adapting the water sector's institutional complexity to meet the growing demand will enhance management power by adopting surface and groundwater, as well as transboundary water management strategies (across river basin boundaries).

Robustness of management power (R_P) can be improved by adopting emergency operations plans, by enhancing the urban water managers' capacity to improvise, innovate, and expand operations when needed, as well as by installing national support programs that can be accessed in the case of an emergency situation. To make the scenario more cautious, Ulaanbaatar's global city ranking is reduced, which would result as a consequence of political and economic changes leading to a lessened international competition for Mongolia's natural resources, and therefore, a reduced willingness of international investors to invest in the country's infrastructure. No change in Community Adaptation (A) is assumed, however, community resilience (R_A) is strengthened by ensuring access to alternative water resources in Ger areas, such as through the promotion of a (regulated) private market. In addition, citizens' access to information about the water sector should be improved, and water should be adequately treated to make it drinkable at the household level whenever necessary.

Ulaanbaatar is faced with a range of threats, and within the short-term a significant reduction cannot be achieved. Instead, focus should be on avoidance of letting additional threats emerge, such as the risk of water contamination through industrial spills (e.g., from mining) by keeping such businesses away from the city's catchment area (see *Appendix 1* and (Krueger et al., 2019) for the estimation of risks). This moderately ambitious future trajectory leads to an improvement in service s as marked by the * in Fig. 23.

Table 1: Ulaanbaatar's Capital Portfolio Assessment (CPA) for current conditions (o), and a future scenario based on a smart investment strategy leading the system towards adaptivity (*). C = capital availability, R = capital robustness. For details on the CPA method, see *Appendix 1* and (Krueger et al., 2019).

Capital	Availability metric	C		Robustness metric	score		R		Management metric	score		M		risk score
		o	*		o	*	o	*		o	*	o	*	
Water resources (W)	water stress level	0.51	0.62	storage-to-flow	1	2	0.55	0.8	EFP	-0.29	-0.29	-0.46	-0.46	0.5
				source diversity	2	3			WFP_global	0.17	0.17			
				import dependence	4	4			WFP_local	0.35	0.35			
									WD	0.26	0.28	0.35	0.42	
				use-resource	1	2			RD	0	0.2			
				water quality	1	3			RE	0	0.1	MW	MW	
									EPI	0.35	0.45	-0.06	-0.02	
Infra-structure (I)	status (coverage & quality)	0.32	0.43	anticipatory maintenance	0	0	0.33	0.44	% sanitation	0.41	0.55	0.32	0.32	0.5
				emergency solutions f. power failure	0	0			decentralization	0.55	0.41			
				intersector coordination	0	1			Integration:					
				supply continuity	1	1			sanitation>85%	0	0			
				monitoring system	0	0			reuse	0	0			
				materials age	1	1			energy-from-waste	0	0			
				critical node redundancy	0	0			nutrients-from-waste	0	0			
				source decentralization	0	0			solar-for-warm water	0	0			
				emergency zone isolation	1	1								
Financial capital (F)	budget (required/available)	0.27	0.36	cost recovery	0	1	0.67	1	FDM	0.24	0.24	0.76	0.76	0.67
				city income level	1	1								
				energy autonomy	1	1								

Capital	Availability metric			C		Robustness metric	score		R		Management metric	score		M		risk score
				o	*		o	*	o	*		o	*	o	*	
Management Power (P)	metric score	o	*	0.25	0.58				0.25	0.75	Governance central.	0.5	1	0.25	0.79	0.67
	communication	1	1			emergency operations planning	0	1			Coord. management:					
	feedback-loops	1	1								sanitation	1	1			
	inter-sector coordination	0	1								drainage	0	0			
	training & innovation	0	0			capacity to improvise, innovate, expand operations	0	1			energy & industry	1	1			
	participatory governance	0	1													
	customer service	0	0								traffic & mobility	0	0			
	integrity	0	0													
	administrative losses	0	0			national support programs for disaster recovery	0	1			recreation	0	0			
	urban-urban/urban-rural management	0	0								urban ag.	0	0			
	transboundary agreements	0	1								amenities	0	0			
	groundwater management	0	1			city ranking	1	0			education	0	1			
	surface water man.	0	1								participatory man.	0	1			
Community Adaptation (A)	self-/ private water services			0.2	0.2	median income level	0	0	0.29	0.71	engagement	0	0	0.59	0.59	0.5
						alternative water services	0	1			demand man.	1	1			
						household storage	0	0			awareness	1	1			
						information access	0	1			Gini coefficient	0.32	0.32			
						community structures	1	1								
						in-house water treatment	0	1			demographic control	0.61	0.61			
						access to water sources	1	1								
Total	CP :			0.27	0.48	RP :			0.52	0.95	MP; *risk :*			0.37	0.49	*0.57*

4.4 Panarchy

[A version of this chapter will be submitted for review to a scientific journal.]

The key to sustainability lies in adequately addressing panarchy: the processes emerging from cross-scale and cross-sectorial interactions.

In the discussion above, Panarchy has been kept somewhat oblique; referred to as 'cross-scale and cross-sectorial effects', and framed under the general term of 'risk'. Here, I elaborate on the concept and on how it can help take a different perspective on the sustainability of urban development in the context of environmental change.

The term was coined by Gunderson and Holling (2002), who proposed that resilient systems follow the four phases of the adaptive life cycle (**Figure 24a)**: The exploitation and growth phase is followed by the conservation phase, during which processes are reasonably predictable (Walker et al., 2004). As the conservation phase continues, competed-for (ecological or economic) resources become increasingly locked up, power distribution and institutional settings rigidify, entrenching the status quo (Pritchard & Sanderson, 2002). This phase is *"eventually followed by a chaotic collapse and release phase that rapidly gives way to a phase of reorganization [...] during which innovation and new opportunities are possible"* (Walker et al., 2004). Maladaptive systems deviate from the adaptive cycle, and can end up in poverty or rigidity traps (Holling et al., 2002). In rigidity traps, resources and efforts are focused to adapt to specific external forces and internal demands, which leads to highly connected, self-reinforcing, and inflexible systems (Carpenter & Brock, 2008). Systems in poverty traps have a lack of, or are unable to exploit available resources. Negative feedbacks prevail, preventing these systems to escape the poverty trap (Krueger et al., 2019). Resilience of these systems is revealed by rotating Fig. 24a) around the x-axis, which results in **Fig. 24b).** As the phases move from exploitation and conservation towards the release phase, the system loses resilience. In the mal-adaptive rigidity trap the system stays in the resilient domain by building robustness.

Similar to the nested hierarchies of scale-free networks discussed in Section 3, the concept of panarchy entails that processes occurring at different scales are nested in and linked to processes acting at both larger and smaller scales. Faster, smaller-scale processes are able to test, invent, experiment and occupy niches (of innovation, ecological, social, etc.); the slower levels conserve accumulated memory of the past. The interactions across scales in the adaptive cycles of panarchy combine learning with continuity (Holling et al., 2002, p.76). This is illustrated in **Fig. 24c**). The word "revolution" indicates that a process in one panarchy can cascade into the next larger and slower level. This can trigger a crisis at the larger, slower level. In this way, fast and small events can overwhelm slow and large ones. Another type of cross-scale interaction is indicated by the downward pointing arrow labeled "memory": Once a system at one level has collapsed, the opportunities and constraints for its renewal are strongly organized by the conservation phase of the next larger and slower level (Holling et al., 2002). It is this connection among fast and slow processes, large and small scales that support each other in the renewal and conservation that the authors suggest being the process underpinning sustainability.

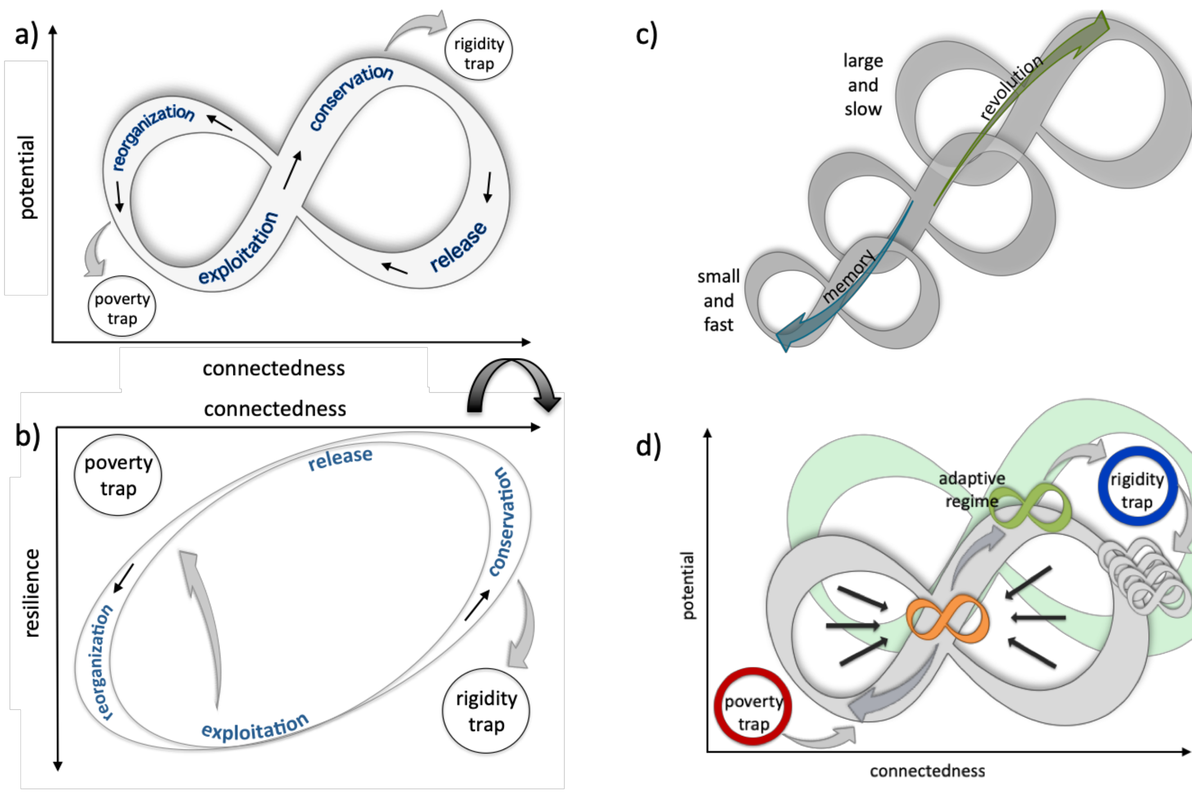

Figure 24a): Adaptive cycle and maladaptive deviations (traps); **b)** Rotation of a) around the x-axis reveals resilience perspective; **c)** Interacting levels of the panarchy; **d)** Phases of the adaptive cycle resulting from urbanization occur in the front loop. Illustrations a-c) based on (Gunderson & Holling, 2002).

The application of the adaptive cycle and panarchy concepts for assessing urban water security, resilience and sustainability is summarized in **Figure 24d)**. The large, grey adaptive cycle represents the local or regional human-environment interactions without urbanization ("natural adaptive cycle"). Moving through the different phases of the adaptive cycle leads to oscillation between conditions of low connectedness, low potential and high resilience, and conditions to their opposites. We can think of this as varying water availability resulting from climatic fluctuations, such as wet and dry periods with corresponding periods of high and low productivity. The introduction of infrastructure aiming to provide stable water flows reduces variance, which corresponds to the "shrinking" of the adaptive cycle (black arrows indicate a size reduction of the grey adaptive cycle down to the orange adaptive cycle). At the same time, processes of urbanization and population growth lead to accelerated change dynamics, so that system conditions oscillate at higher speed within a smaller range of potential (y-axis). This was pointed out by Bettencourt et al. (2007) and discussed in Section 3.3, showing that urban population growth leads to an acceleration of innovation cycles. During the transition phase, which corresponds to the exploitation to conservation phase of the adaptive cycle (front loop), although variance is reduced the system experiences setbacks with periods of release and reorganization until it has developed to full potential with high levels of security and robustness. Optimizing for performance moves the cycle upward towards higher potential and connectedness from source to city and within the city to the customer towards water security.

Technological progress and globalization allow cities to extend their water reach. As cities reach beyond their boundaries, including the import of water and ecologically intensive products, the urban system becomes unsustainable and disconnects from the large adaptive cycle, moving into a rigidity trap (blue). The rigidity trap emerges as cities increasingly invest into inflexible, unsustainable infrastructure. Detached from the adaptive cycle of the environment, ignorance of the panarchy component may lead to unforeseen consequences resulting from cross-scale interactions. The decline of a regime (release phase) can be catastrophic failure caused by external shocks, such as natural disasters or war. The smaller adaptive cycles (grey) indicate that once the “natural” adaptive cycle (e.g., climatic or other environmental conditions) is no longer able to support the current urban regime, the system can be incrementally transformed, if adequate action is taken before collapse is induced.

The alternative path downwards, back-tracking the front loop in the direction of the poverty trap (red) marks the trajectories of cities that cannot keep up with population growth and environmental degradation. In the poverty trap, cities are unable to marshal the required capitals to provide services. In the adaptive urban regime (small green adaptive cycle), continuous adaptive management is required for maintaining the balance between conservation and release.

Interaction among the urban system and other system(s) in the panarchy are what can cause system transformation or collapse in the long-term. The disconnect between the system in the rigidity trap and the larger panarchy (e.g., local or regional natural adaptive cycle) creates a false sense of security, as variance seems to have been eliminated. However, as Carpenter and Brock (2008) demonstrated, reduced variance at high frequencies guarantees an increase at low frequencies. As Fig. 24d) suggests, this could be a result of the change in scale from the natural adaptive cycle (grey) to the urban adaptive cycle pushed upward towards higher potential (green & blue). In urban water supply systems, the introduction of infrastructure and institutions reduces variance. However, unsustainable management (pumping beyond renewable rates, changes in land-use) can lead to catastrophic system failure in the long-term.

The next level of the panarchy is illustrated by the large, pale green adaptive cycle in the background, which represents systems at global scale, such as the global climate, global population, global food production, or the global trade system. Other possible levels of panarchy are different sectors interacting, such as the water sector with the food and energy sectors, which are all interdependent, and a disconnect between them can lead to unexpected shocks.

Figure 25 shows the urban water systems of Mexico City, Singapore and Ulaanbaatar in the context of the adaptive cycle and panarchy. A marker on the global adaptive cycle in the early release or decline phase (π_G) schematically indicates the current state of the global environmental system (e.g., global state of ecosystems). The pale grey adaptive cycle is the local or regional environmental system, while the colored cycles represent the cities' water supply systems (blue, green, red).

Mexico City's trajectory shown in Fig. 25a) starts in 1381, dating the first recorded aqueduct by the Aztecs. The decline ("release") phase of this cycle (dark grey in the background) begins with the arrival of the Spanish in 1521. Destruction of the existing infrastructure provided opportunity to reorganize, although the new system was less successful in terms of resilience and sustainability than that of the Aztecs. The second cycle begins shortly after this conquest (~1521), and reaches its highest potential in 1554, before a great flood hit in 1555. The trajectory from this date onwards is shown here caught in a maladaptive rigidity trap; repeated flooding and recovery events and decisions to stay in the city, build more infrastructure to sustain a growing population is illustrated by arrows pointing down indicating decline, and, instead of entering a new adaptive cycle, the system climbs back up to its earlier position. In spite of damage from flooding or earthquakes, resources are not released, and the system is not reorganized. Instead, the system remains locked-in, which prevents renewal for transformation (Marlow et al., 2013). The latest arrow pointing upwards in the rigidity loop represents the construction of the Gran Canal, built in order to relieve the city of its sewage and excess stormwater (1900), as well as the two major water import projects (Lerma, 1970, and Cutzamala, 1982).

The difference between adaptation and transformation is illustrated here: Within the rigidity trap, the city has repeatedly (mal-) adapted to increasing demand and the degradation of existing infrastructure by reinforcement of the existing system. However, crucial to long-term sustainability is allowing the system to enter the backward loop after a decline phase, where resources become available for reorganization. In this way, transformation can take place and the system can enter a new forward loop after adaptation to changed external conditions. For centuries Mexico City has resisted entering the back-loop, which would allow the city to develop a new water management paradigm.

The time scales for adaptation and transformation differ by orders of magnitude, and the likelihood of transformation, under current urban planning approaches, is extremely low. Mexico City went into the back-loop after destruction and re-settlement by the Spanish, but this transformation turned out to be maladaptive ("mal-transformed"?), and was only initiated by destruction. In contrast to Mexico City, the 1997-2010 drought in Melbourne induced a paradigm shift in thinking. This may be the start of an incremental system transformation, such as indicated by the small grey adaptive cycles in Fig. 24d). Such a "smooth" dissolution of the current management paradigm describes the slow transition towards a back-loop, in which additional resources become available, which, if adequately taken advantage of, may allow a full system transition into sustainability.

Fig. 25b) shows the up- and downward phases of Ulaanbaatar's trajectory in the transition phase, the scenario for 2030 (*) developed in Section 4.3, and an arrow pointing towards the poverty trap marks the city's current position. It is from here that, once resources are made available, cities have the highest potential for reorganization, and for choosing a different pathway for developing urban water systems that are designed to be more sustainable from the start. In contrast, cities with extensive water systems are locked into conditions with long legacies and inflexibility for adaptation. Population growth and economic uncertainty have been reinforcing poverty for the majority of Ulaanbaatar's population. The city is also globally unsustainable, which arises from the fact that in its cold and arid climate, few resources are locally available, and are therefore imported. Unless local management issues are adequately addressed, there are few chances that the global footprint would be reduced.

Fig. 25c) represents Singapore's water trajectory, which follows the front loop, marking its transition starting in 1819, with a few setbacks during World War II, and resolves in an adaptive cycle at high potential (services). Within the small, green adaptive cycle the city is adapting to changing demands and access to water resources locally. It is also in a position, where its globally unsustainable, local adaptation negatively impacts the global adaptive cycle representing, e.g., global climate. This is indicated by the large distance (δ) of the local (grey and small green) and global (large green) adaptive cycles. The impacts of panarchy caused by cascading effects of a changing global climate, sealevel rise, changes in oil prices, global food production and trade, etc., are likely to have a major impact on Singapore's water supply system.

The adaptive cycles' position along the y-axis indicates each city's relative local and global sustainability (large grey and green adaptive cycle, respectively), where the dashed line represents MP_{global}, and the solid line MP_{local}. The urban water systems' current condition is indicated by the double-dashed line ('CP, today').

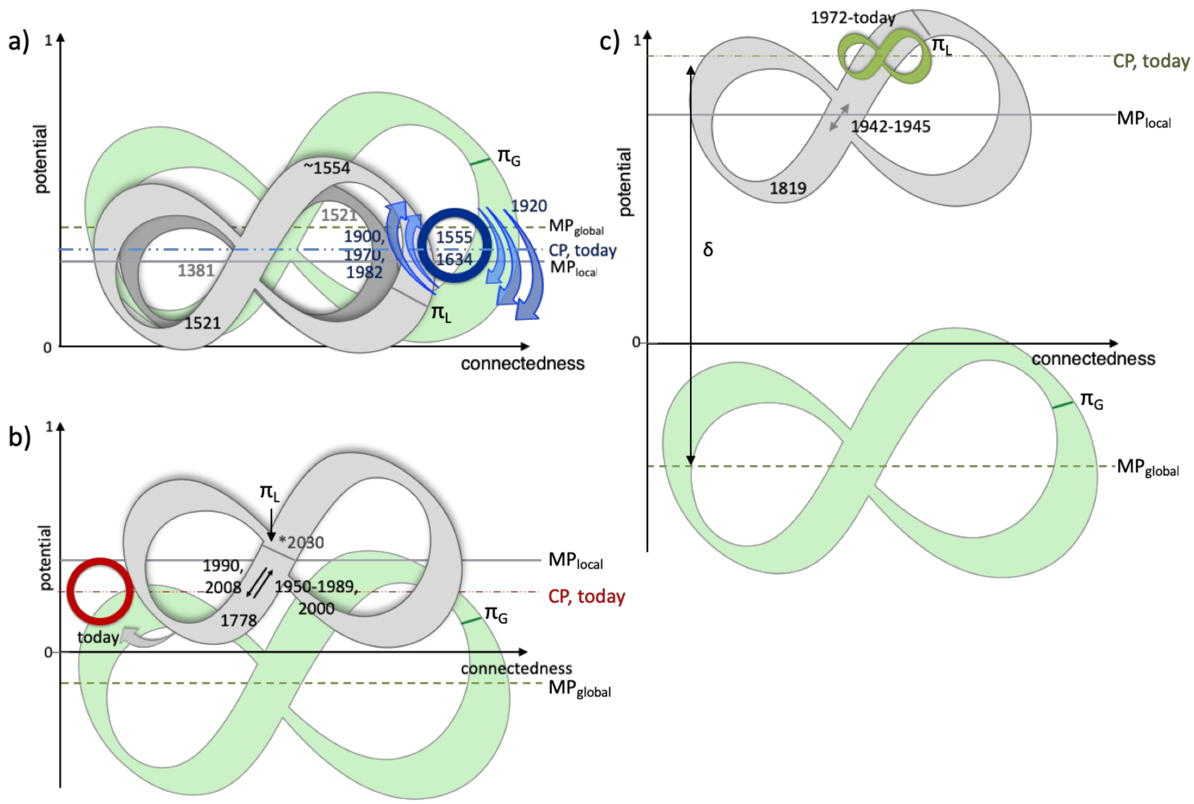

Figure 25: Adaptive cycles and panarchy of a) Mexico City, b) Ulaanbaatar, c) Singapore.

Consideration of panarchy in the conceptual assessment of urban water systems visualizes the connection of urban water security, resilience and sustainability. Security and resilience are represented by the system's position within the local/regional adaptive cycle with security explained by the position along the y-axis 'potential', resilience in the 'resilience'-axis (see Fig. 24b): A system has a certain level of resilience relative to its own scale, i.e., the respective, local/regional adaptive cycle, and only as long as cross-scale and cross-sectorial effects from the panarchy remain absent. Sustainability is explained by the relative position of the local and global systems. The positions are relative from a local perspective: they represent each city's management sustainability. The global state of the system relative to itself is indicated by the marker line on the global adaptive cycle labeled 'π_G', and 'π_L' on the regional/local adaptive cycle marks the current phase of that system. Singapore's local MP is high, which is why the local 'natural' adaptive cycle (grey) appears at relatively high potential (Fig. 25c). Its global MP, on the other hand, is very low, as indicated by the low position of the global adaptive cycle (pale green). The distance between the values of MP_{global} and CP indicated by the vertical arrow labeled "δ" indicates the potential shock magnitude caused through the impact of global panarchy resulting from the risk of global unsustainability. Given that global ecosystems are positioned in the early decline phase, if they do collapse, the potential impact on Singapore's water supply system caused by changes in different sectors and on different scales (e.g., food and energy security, sealevel rise and other climate change impacts, etc.) could be disastrous. Whether or not these impacts would hit Singapore at full force depends on 1) Singapore's response to such shocks, and 2) how these impacts are distributed globally.

Any management measure can only be implemented locally, and will be subject to local response. So while direct management of panarchy is not possible, local management everywhere will impact global processes. Management measures should be taken to impact the local structure of the stability, resilience and Budyko landscapes as discussed in Section 4.1-4.3 (changing latitude, MP, or resistance, RP) or the state of the system (precariousness, CP), and responding to changes in the landscape (response to effects of panarchy). Awareness of the entire landscape / the global and regional adaptive cycles in the panarchy helps taking decisions that are adequate to a system's current position within the larger landscape; sustainable management practices allows sensing, anticipating and responding to changes across scales and sectors. An example of this is the changing climate, in response to which management measures can only take place locally, e.g., by reducing CO_2 emissions of various activities. Changing the landscape and effects of panarchy takes international regulation and concertation of local efforts.

5. Designing Secure, Resilient and Sustainable Urban Water Systems

"A large part of the problem lies in the way we have organized our intellectual activities. [...] The academic disciplines are today still very isolated from each other and this contributes to the difficulty of addressing the questions posed here." (Costanza et al., 2015) p. 24

The unsustainability of our practices regarding the human-environment relationship is a universal problem related to the unconstrained and globalized character of our lifestyles. Faced with the threats of climate change and other global change impacts, including the increasing scarcity of resources, cities that can afford to, access water resources from increasingly distant locations beyond the urban area, and "*remotely impact millions of people, economy and aquatic ecosystems. For every three urban residents living in a city that avoids water deficit via cross-basin transfer, there is one person affected remotely in the source basins*" (Floerke et al., 2018). These direct remote impacts are exacerbated through the import of water-intensive products, and the export of water polluting production through virtual water trade, leading to water and ecological footprints that are already exceeding the planet's carrying capacity (Holden et al., 2014; Jaramillo & Destouni, 2015). The UN World Water Assessment (2015) predicts that by 2050, more than 5 billion people will live in water scarce areas, and will face water shortages at least once per month, on average. Continuing urban growth, and increasing competition among cities and sectors will force cities to turn towards less resource-consuming management options. Cities that are in the process of building urban water systems to provide services to growing populations must avoid "Business As Usual" trajectories.

Here, I draw conclusions from Sections 1-4 on how to design secure, resilient and sustainable urban water systems (Section 5.1). Section 5.2 discusses the broader context for this work and existing efforts in which new avenues are developed for urban transformations to sustainability. Section 5.3 closes with an outlook for future research.

5.1 Synthesis

The balance of security, resilience and sustainability is an important condition for urban livability in the present and the future: Urban livelihoods depend on the security of water and other services provided by functioning infrastructure, institutions and ecosystems (Padowski et al., 2016). Resilience is necessary for recovery from shocks and disturbances, as well as for adapting to changing demands and environmental conditions (Gunderson & Holling, 2002; Klammler et al., 2018). Sustainable management ensures the long-term viability of security and resilience, and is required for long-term well-being (Bai et al., 2016; Blythe et al., 2017; Costanza et al., 2015; Rockström et al., 2009).

It was shown here that urban water security, defined as the state of water supply services received by the citizens, is determined not only by the availability of water resources, financial capital and infrastructure, but also by adequate management institutions, which are able to respond to changing demand, environmental conditions and aging infrastructure systems. Where public services result in water service deficits, citizens adapt and make up for the city's inability to provide adequate services. However, this leaves the urban community in a precarious situation with high vulnerability regarding health and socio-economic conditions, which feeds back into the cities' overall socio-economic well-being (Béné et al., 2014; Eakin et al., 2016; Gerlach & Franceys, 2009; Rosenberg et al., 2008; Srinivasan et al., 2010b; Wutich & Ragsdale, 2008). Moving away from the pathway that leads to degrading life-support systems and rising inequality requires a focus on ensuring adaptive capacity of all citizens.

Resilience, defined as the dynamic behavior of the system in response to disturbances, is determined by the frequency and magnitude of recurring shocks, as well as the system's robustness and preparedness to deal with those shocks. Water security and resilience tend to co-evolve, making their level of performance somewhat predictable. However, two types of threats challenge urban water security and resilience: 1) slow decline through incremental degradation of infrastructure and institutions; 2) panarchy-driven cross-scale and cross-sector risks, whose probability increases through (globally) unsustainable practices. Such unsustainable practices include pushing the degradation of life-supporting ecosystems beyond safe boundaries for human well-being (Steffen et al., 2015; Vörösmarty et al., 2010). While the services from ecosystems, such as freshwater, are commonly considered renewable, it is crucial to acknowledge that renewability is non-stationary. This means that the degradation of ecosystems reduces their ability to provide the desired services. In addition, total renewable rates are divided by total population numbers. Unless population growth is limited, resource availability per capita will continue to diminish (Ehrlich et al., 2012; Song, 1972). An increasingly crowded planet will face stronger competition for resources, putting demand management at the heart of any solution strategy.

The (engineered) internal spatial patterns of cities are functionally organized in the same way that natural and human systems are (Batty, 1994; Masucci et al., 2014; Yang et al., 2017). As a consequence, their vulnerability is determined by mechanisms and processes that are also comparable to those found in nature and society: In unconstrained systems, the mechanisms of growth and resource (re-) distribution are multiplicative (in networks: preferential attachment), which leads to 1) massively large systems (giant connected components), which require ever-growing resources for their maintenance; and 2) inequality, which in the extreme, results in bi-modal distributions (polarization) (Bettencourt et al., 2007; Scheffer et al., 2017). The drawback of unconfined growth is that vulnerability and the consequences of failure increase with size and with inequality (D'Souza et al., 2014). Therefore, managing for resilience demands limiting system size and re-distributing resources among citizens to limit inequality.

Urban growth is driven by the economies of scale, and limiting urban growth is challenging. To optimize for resilience in spite of growth, urban planning and management should target spatial (topological) modularity organized in nested hierarchies. As a consequence of the maximization of service performance as an objective function and due to the topology of rigid systems, short-term and small-scale variability is eliminated, which necessarily leads to large-scale (high magnitude) and long-term variability (Carpenter et al., 2015). Managing for resilience should allow for short-term and small-scale variance, which, combined with the existence of diversity and the presence of nested hierarchies (modular topology), enhances the recovery process. Failure to control for growth (in size and demand) and inequality (described by its topology) leads to two kinds of traps: the poverty and the rigidity trap, which can also be considered as traps of local and global unsustainability, respectively. Local unsustainability results from local/regional degradation of ecological, social and engineered systems (Cumming et al., 2014). Global unsustainability results from so-called "global upscaling" by which the consequences of unsustainable consumption and lifestyles are externalized at the cost of people and ecosystems elsewhere. The way in which these challenges are addressed will determine the future of urban water security and resilience.

Although sustainability is a desirable goal and has been on the international agenda for decades, unsustainable practices persist (Lafuite & Loreau, 2017; McCormick et al., 2013; Olsson et al., 2014). Ignorance of urban unsustainability is due to its "invisibility" promoted by the interception of the human-environment relationship, which in urban systems is mediated through infrastructure (Bowker & Star, 1999). Complexity in urban systems is conventionally tackled through compartmentalization, which in turn requires coordination. Interdependencies of increasingly large and complex urban systems requires high capacities for system maintenance, as well as for coordination among urban sectors, system components and stakeholders. The lack of information flow can lead to a misalignment of stakeholder perceptions, which in turn can misguide and complicate decision-making and management, such as the implementation of demand-management measures (e.g., water pricing versus willingness to pay, practicing efficient water use, water reuse, etc.). Mutual awareness of perceptions and their motivation can be improved by facilitating information flow and promoting transparency of decision-processes.

The conceptual division between nature, humans and the engineered systems that humans create in their interaction with nature, obscures their unity (Wilson, 1998). It obstructs our ability to appreciate the knowledge at our hands to understand the mechanisms, patterns and trajectories, as well as how to interact with ("manage") CNHE systems. Examples of synthesis on topological patterns and processes mentioned above are complemented by a synthesis of hydrological and social-ecological system understanding about the evolution and trajectories of urban water supply systems. In spite of varying contexts, histories and path-dependencies of urban water systems around the world, the underlying mechanisms, optimization for the same objective function (i.e., maximization of water supply services) and a limited set of constraints reduces the complexity of observed heterogeneity of urban water challenges. Cities fall along a continuous gradient reaching from insecure and non-resilient to secure and resilient, and their sustainability (i.e., long-term trajectory) largely depends on how urban water security and resilience are managed globally.

5.2 Pathways

There is a wealth of engineering solutions for the design and examples of implementation of sustainable urban water systems (Hering et al., 2013; Lahnsteiner & Lempert, 2007; Larsen et al., 2016; Mulhall & Braungart, 2010; Ray et al., 2012). A variety of technologies for water reuse, fostering of the water-energy-food nexus (Allan et al., 2013; Dermody et al., 2018), decentralized and modular systems, and the management of urban service sectors using concepts and methods derived from the circular economy and life-cycle assessments exist (Cousins & Newell, 2015; Fagan et al., 2010; Lane et al., 2015; Lemos et al., 2013; Loubet et al., 2014). The circular economy aims to fully close the life-cycle loop, based on three principles: "waste is food", i.e. everything is a resource for something else, 2) "using current solar income", i.e. energy should be renewable and primarily solar, and 3) "celebrate diversity", acknowledging that narrowing down applied solutions increases vulnerability (Niero et al., 2017b, 2017a). However, implementation lags behind due to lock-in and legacy in rigid urban systems (Marlow et al., 2013), hesitation due to unknown trade-offs, potential negative feedbacks and a lack of trust across scales (Ostrom, 2014), the need for accommodating conflicting interests, and, most importantly, the focus on short-term (mostly financial) benefits rather than benefits of overall societal well-being. Whether or not cities can or want to implement the necessary measures and launch the proposed strategies is contingent on several factors, including perceived and actual pressures on urban livability, current conditions, and the adaptive capacity of each city (Dong et al., 2018; OECD, 1993).

Recommendations on improving urban resilience need to consider the factors contributing to adaptive management, if adaptation measures are to be successfully implemented. A growing body of literature is suggesting that it is the governance system with its institutional setup that determines the success and failure of urban sustainability transitions (Ashraf et al., 2016; Kiparsky et al., 2013; Marlow et al., 2013; McCormick et al., 2013; Meerow et al., 2016). In addition, important aspects of solution options, such as the adequate scale of implementation of decentralized and modular systems remain unspecified, because experience is lacking (Spiller et al., 2015). Experience requires experimentation and learning from incremental changes (Carpenter et al., 2015; Ferguson, Brown, Frantzeskaki, et al., 2013; Marshall et al., 2012; Moore et al., 2014; Pahl-Wostl et al., 2007), which at the same time is the least destructive way of achieving transformation (as opposed to catastrophic failure followed by slow recovery or collapse). Where the solution space suggests a range of options with varying degrees of societal and ecological sustainability, “choice architecture” strategies offer a promising pathway to behavioral change towards sustainability (Creutzig et al., 2018; Weber, 2017).

Cities are complex adaptive systems, which show emergent behavior resulting from self-organization (Batty, 2013; Bettencourt & Kaur, 2011; Bettencourt et al., 2010; Brelsford et al., 2017). This implies that top-down command and control management and transformation will not be successful (Hill, 2013; Webb et al., 2017). Research on cities as complex adaptive (eco-) systems is growing (Elmqvist et al., 2018; Ferguson, Brown, & Deletic, 2013; McCormick et al., 2013; McPhearson et al., 2016; Webb et al., 2017), and suggests that incremental transformation of urban systems is achieved by a process called "urban tinkering" (Elmqvist et al., 2018) that involves such experimentation, embraces diversity, and promotes the principles of social-ecological resilience (Ostrom, 2009) into social-ecological-technical systems (Bai et al., 2016; Webb et al., 2017).

Increasing diversity of urban habitats and managing cities as urban ecosystems (Collins et al., 2000; Grimm et al., 2008; McPhearson et al., 2016) has the potential of making cities more sustainable and thus, more secure and resilient in the future. While this means that there will be a higher likelihood of avoiding devastating catastrophes and complete system failures, it also implies higher variance of service security occurring locally and at short time scales (Carpenter et al., 2015). Modular setups of both, infrastructure and institutions promise to be the most robust and resilient structure for dealing with shocks and variability (Nordbotten et al., 2018; Ostrom, 2014). However, the evolution of urban water systems is not only contingent on (mal-) adaptive management (Barnett & O'Neill, 2010; Juhola et al., 2016; Marlow et al., 2013), but also on the extent and speed of climate and other global change processes, which produce dynamic shock regimes (Klammler et al., 2018; Krueger et al., n.d.).

5.3 Horizon

The research presented here investigated the dynamics of social-ecological-technological systems (SETS), and how adaptive and maladaptive management practices determine the future evolution, resilience and sustainability of human-water-ecosystem relationships (Barnett & O'Neill, 2010; Juhola et al., 2016). The objective of the present work was to clarify confounding concepts of urban water supply security, resilience and sustainability, to deliver reliable methods for their quantification, to build bridges across disciplines and to provide integrated, quantitative and transferrable approaches. This type of synthesis leaves space for further elaboration of methods and details, or for testing alternative models and hypotheses.

The systems dynamics model was developed and parameterized for the assessment of security and resilience, and does not include the dynamic modeling of the sustainability dimension. Expanding the model or developing alternative models to include sustainability would produce additional system understanding about the long-term trajectories and the behavior of rigidity traps over time. While the approach includes interfaces with other sectors, its focus is on urban water supply. The general framework should be transferrable to other sectors, and can be expanded to assess water security more broadly (Garrick & Hall, 2014; Hoekstra et al., 2018), or water-food-energy-nexus systems (Allan et al., 2013; Bijl et al., 2018; Dermody et al., 2018; Scott et al., 2011), relating developments in the water sector to developments in other sectors and vice versa.

The combined effects of decisions taken in the present (or the past) and their feedbacks with processes in the natural environment, such as the variability of rainfall and runoff processes (Pascale et al., 2016), degradation of soils and ecosystems (Basu et al., 2010; Musolff et al., 2017; Park et al., 2013; Webb et al., 2017; Zanardo et al., 2012), and technological advancements (Brown et al., 2009; Kiparsky et al., 2013; Parolari et al., 2015), determine the sustainability and path-dependent trajectories of urban communities (Ferguson et al., 2014; Tellman et al., 2018). The evolutionary processes of urban water systems and decisions linked across local and global, as well as short- and long-term scales are not sufficiently understood in a quantifiable (probabilistic) way (Clift et al., 2017). The mutual impacts and feedbacks of management choices and the consequences of competition for space and resources, as well as among socio-economic, environmental, technical and political changes, should be explored in more detail and for additional case studies, as urban areas continue to expand (Chen et al., 2015; Grimm et al., 2017; Siciliano & Urban, 2017).

Patterns and processes emerging from intra-urban heterogeneity of urban water security and resilience (Brelsford et al., 2017), its impacts on social inequality (Dragulescu & Yakovenko, 2000; Yakovenko, 2013), and how such patterns and processes impact city-scale urban water security, resilience and sustainability warrant further research. Currently global change, including climate change, degrading ecosystems and dwindling resource availability (Rockström et al., 2009) coincide with societal developments that are polarizing communities around the world (Inglehart & Norris, 2016). There is growing knowledge about complexity, resilience, tipping points, and hysteresis effects in the environment (Batty, 2013; Gao et al., 2016; Gunderson & Holling, 2002; Lade et al., 2013; Ludwig et al., 1978; Touboul et al., 2018), as well as a wealth of engineering solutions and best-practice examples for managing transitions (Ferguson, Brown, Frantzeskaki, et al., 2013; Ibisch et al., 2016; Larsen et al., 2016; Moore et al., 2014; Park et al., 2011). However, the future of our planet is not only determined by what we can or should do, but increasingly by the world we want to live in, and the price we are willing to pay for it, i.e., the drivers of human behavior (Bodin & Crona, 2009; Varoufakis, 2017), whose integration into models of environmental change processes deserve more focused attention. Agent-Based-Modeling, informed by big data available through satellite data and social media, as well as census data, and those gathered in field and household surveys, can be a useful tool for exploring intra-city patterns and processes emerging from the interaction of agent behavior (Barros & Sobreira, 2002; Guo et al., 2017).

Research that targets the advancement of knowledge about and practice of transformation to sustainability, in which systems will depend on fewer resource inputs and pollutant outputs should be promoted (Elmqvist et al., 2018; Marlow et al., 2013; McPhearson et al., 2016). Transdisciplinary research can be a crucial ingredient into the necessary experimentation, observation, learning and adaptation of the complex adaptive systems that cities represent (Blythe et al., 2017; Webb et al., 2017). Model and assessment results presented here should be verified and updated with local stakeholders, before additional steps exploring concrete measures to be implemented in specific cities are carried out in co-designed and co-produced research efforts.

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Appendices

Appendix 1: Quantification of urban water supply security (published manuscript)

Appendix 2: Resilience modeling of urban water security (manuscript in review)

Appendix 3: Generic patterns in the evolution of urban water networks (published manuscript)

Appendix 4: Assessment of sustainable management based on CPA

Appendix 5: Household survey questionnaire (English/Arabic)

Appendix 6: Key informant interview questionnaire

Appendix 7: Data for global urban water system assessment

VITA

Elisabeth Krueger's research interest is in the evolution of human-environment interactions and in contributing to the transition of society towards sustainability. Her work focuses on interactions and dynamics of coupled social-ecological-technical systems and the emergence of resilience. Her research is driven by the aim to synthesize knowledge about generative mechanisms and emergent patterns in nature, society and technology, as well as understanding trade-offs across sectors and scales (individual-collective; short- to long-term; local-global). She has worked with researchers, managers and urban planners in several countries, including in Europe, North Africa and Asia. Before completing her PhD, she spent six years as a research manager for national and international interdisciplinary water research projects at Helmholtz Centre for Environmental Research – UFZ in Germany.