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Resilience Dynamics of Urban Water Supply Security and Potential of Tipping Points

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Key Points:

- Analyses using data-model synthesis of seven global cities reveal coevolution of security and resilience in urban water supply systems
- Global and climate change with increasing, unpredictable shocks can push urban water systems across tipping points
- Resilience emerging from community adaptation is highly variable across and within cities, leading to high inequality and precariousness

Supporting Information:

- Supporting Information S1

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(continued)

Abstract Cities are the drivers of socioeconomic innovation and are also forced to address the accelerating risk of failure in providing essential services such as water supply today and in the future. Here, we investigate the resilience of urban water supply security, which is defined in terms of the services that citizens receive. The resilience of services is determined by the availability and robustness of critical system elements or “capitals” (water resources, infrastructure, finances, management efficacy, and community adaptation). We translate quantitative information about this portfolio of capitals from seven contrasting cities on four continents into parameters of a coupled system dynamics model. Water services are disrupted by recurring stochastic shocks, and we simulate the dynamics of impact and recovery cycles. Resilience emerges under various constraints, expressed in terms of each city's capital portfolio. Systematic assessment of the parameter space produces the urban water resilience landscape, and we determine the position of each city along a continuous gradient from water insecure and nonresilient to secure and resilient systems. In several cities stochastic disturbance regimes challenge steady-state conditions and drive system collapse. While water insecure and nonresilient cities risk being pushed into a poverty trap, cities which have developed excess capitals risk being trapped in rigidity and crossing a tipping point from high to low services and collapse. Where public services are insufficient, community adaptation improves water security and resilience to varying degrees. Our results highlight the need for resilience thinking in the governance of urban water systems under global change pressures.

Plain Language Summary We evaluated the resilience of global urban water supply systems, including in economically advanced cities and those characterized by a prevalence of informal settlements lacking basic infrastructure services. Global change challenges urban resilience with more frequent floods, droughts, population growth, and competition for resources. We demonstrate that urban resilience requires the availability of financial and other “capitals” (water, infrastructure, and efficient governance institutions) as well as robust responses to extreme events. Application of a system dynamics model shows the impact of and recovery from repeated shocks for each city, and that tipping points may be crossed, if changing conditions are not adequately addressed. When public water supply services fail, citizens adapt by buying water from private vendors or storing water in rooftop tanks. However, inequality in adaptive capacity exists within and across cities and leaves citizens in precarious situations. Repeated shocks impair development potential, and cities risk getting caught in a poverty trap. Focus on the development of capitals but neglect of robustness can push cities into a “rigidity trap” characterized by degrading services. Finally, predictions of the timing and magnitude of extreme events will remain unreliable, and managing for resilience will require managers to embrace probabilistic scenarios and uncertain futures.

1. Introduction

Common assessments of urban water supply security quantify the average per capita water availability, whether natural or captured (Damkjaer & Taylor, 2017; Floerke et al., 2018; Jenerette & Larsen, 2006; McDonald et al., 2011, 2014; 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., 2010; Sullivan, 2002;

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Wutich et al., 2017). 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. Of 108 investigated cities in Africa and the United States, 7% remain insecure due to minimal ability to access local and/or imported water. Floerke et al. (2018) produce water security scenarios for 482 of the largest cities worldwide by including the impacts of competitive uses among different sectors. Their results indicate that, by 2050, 46% of cities will be facing water security issues resulting from either surface water deficits or due to competitive conflicts with agricultural water use. In a review on water scarcity more generally, Liu et al. (2017) show that estimates of water scarcity lie in the range of 3–4.5 billion people affected in 2050. In addition to city-scale water insecurity, inadequate provision of available water resources within cities affects a much larger (as yet unquantified) portion of global urbanites. At least 23% of the total urban population worldwide living in informal urban settlements without adequate access to public urban services (883 million people; UN, 2018) can be assumed being affected by water insecurity to a significant degree.

Integrated approaches able to capture water insecurity more broadly have largely been qualitative, theoretical, or based on individual case studies (Eakin et al., 2017; Hale et al., 2015; Romero-Lankao & Gnatz, 2016; Wutich et al., 2017; for reviews see Garfin et al., 2016; Garrick & Hall, 2014; Hoekstra et al., 2018). Recent research has emphasized the need for systematic approaches and metrics that are transferrable and scalable to allow cross-site comparisons, as well as those that combine quantitative metrics with context and qualitative information (Garfin et al., 2016; Wilder, 2016). These articles have also investigated the linkages between water security and adaptive capacity, embracing the concept of "capitals" (also referred to as "assets," "resources," and "desirable determinants"; DfID, 1999; Smit et al., 2001) needed for adaptive capacity (Kirchhoff et al., 2016; Lemos et al., 2016; Varady et al., 2016). In a recent paper, Krueger et al. (2019) presented a quantitative, empirically based and comparative method, which systematically integrates several forms of "capital" for adaptive capacity and provides context to highlight place-based nuances. The method was used to estimate urban water supply security in terms of the actual services that citizens receive, including access, safety (of access and water quality), reliability, continuity, and affordability. In the presented framework ("Capital Portfolio Approach, CPA") the authors proposed that such services require not only the availability of water resources at the city level but also the intraurban infrastructure for storing, treating, and distributing the water; financial capital and governance institutions; and when public services fail, community adaptation to cope with and adapt to insufficient water supply services. The analyses showed that, in cities with high levels of public services, community adaptation remains inactive as long as services perform as demanded. Cities with high levels of water insecurity rely on community adaptation for self-provision of services. Therefore, variability in urban water security is highly dependent on community adaptive capacity. We adopt this notion of water supply security and assess its resilience in response to recurring shocks and disturbances.

The literature on adaptive capacity and water security has revealed tensions in the assessment of water security in static versus dynamic terms (Lemos et al., 2016). Water security approaches, which describe the state of a system at a certain point in time, fall short of capturing the dynamic drivers and adaptive response of human actors suffering from water insecurity. There is also a need for capturing the adaptive response of the human actors and their ability of changing the system. Pathway approaches are suggested to examine the long-term evolution and path-dependent trajectories of water security (Lemos et al., 2016), where risk-based approaches consider the potential changes emerging in an uncertain future (Garrick & Hall, 2014).

One way to address such dynamics is through resilience approaches. Resilience of urban water supply services refers to the dynamic behavior of the system in response to disturbances, its ability to absorb shocks, and its adaptation and reorganization in order to maintain system functions (here water supply services; Gunderson & Holling, 2002; Walker et al., 2004). The resilience of urban water systems is threatened by increasing demand driven by population growth, urbanization, and lifestyle changes, as well as by changing land use and climate conditions (Floerke et al., 2018; Romero-Lankao & Gnatz, 2016). Thus, resilience is an emergent behavior in response to disturbances contingent on the timing and magnitude of shocks and requiring constant adaptive management (Allan & Bryant, 2011; Klammler et al., 2018; Park et al., 2013). Scheffer et al. (2018) discuss how the resilience of complex adaptive systems emerges from the interplay of several networked subsystems, where systemic resilience and the resiliencies of the subcomponents are coupled in a nonlinear way, with the possibility of tipping points. The need for the development of models and integrated system modeling was recognized for the multiple domains of complex, interconnected, and interdependent infrastructure systems (Linkov et al., 2014). The impacts of global change (climate change, urbanization, increasing competition for resources, etc.) and the risk of critical transitions into alternative regimes furthermore not just require adaptation but will also demand the transformation of urban systems, in order to change unsustainable feedbacks (Folke et al., 2010).

Resilient behavior has also been linked to adaptive capacity, which builds on the availability of a range of resources and assets (Brown & Westaway, 2011; Bryan et al., 2015; Eakin et al., 2014; Gallopín, 2006; Milman & Short, 2008; Waters & Adger, 2017). Such integrated approaches highlight the role of social actors, not only for human resilience but also for the resilience of infrastructure systems (Rao et al., 2017). Waters and Adger (2017) present a fine-grained analysis of the relationship between adaptive capacity and resilience of urban informal settlement dwellers with emphasis on the heterogeneity of resilience in space and time based on a range of factors that include determinants of social capital, as well as urban form. While urban resilience at the city scale has been the focus of a number of studies and well-established index methods, they remain static or focused on resilience in general terms (Meerow et al., 2016; Spiller et al., 2015; UN-Habitat, 2017; UNISDR, 2017). We contribute to this literature by quantifying city-scale resilience of urban water supply security, including the heterogeneous role of community adaptation across cities.

Several models have been proposed that capture the dynamics of social-ecological, sociotechnical, and coupled natural-human-engineered (CNHE) systems. Some address specific systems and management responses, for example, reservoir management during flood and drought periods (Baldassarre et al., 2017). Emergence of poverty traps is observed in a CNHE system model that investigates the dynamics of water security-related investment and its interplay with economic growth and risk reduction (Dadson et al., 2017). Muneepeerakul and Anderies (2017) introduce a model that shows how the coupled dynamics of the natural environment, infrastructure, public providers, and resource users driven by financial incentives give rise to the emergence of a governance system. Carpenter and Brock (2008) introduce a generic social-ecological systems model, where low, medium, and high levels of control ("stress") are associated with poverty traps, adaptive capacity, or rigidity traps. The system is forced externally through unexpected shocks, and recovery depends on adaptive capacity. With a similar logic, Klammler et al. (2018) introduced a CNHE system model representing two state variables: (1) critical infrastructure service deficit and (2) adaptive management mobilized to recover services. They show how different model parameterizations can lead to multiple (stable) system states and how sequences of recurring, stochastic shocks can lead to regime shifts from one state to another or force the system into collapse. These existing models provide important insights into the dynamics and resilience of coupled systems. However, they remain theoretical and generic, without empirical application.

Here, we address these gaps by integrating system state, risk, and dynamic response using empirical data. We consider the security of urban water supply as a system state, which is subject to shocks resulting from risks potentially threatening the system state. We follow the definition of security of water supply services provided in the CPA of Krueger et al. (2019), implying security of services in terms of access, reliability, continuity, and safety of water quality and of access to supply. Resilience of the system refers to its dynamic behavior in response to shocks. The dynamic response requires several interacting forms of capital, and the action taken by human actors is the adaptive management marshaled by mobilizing available capital through capital robustness. Our definition of the resilience of urban water supply security is aligned with the definition of urban resilience proposed by Meerow et al. (2016):

> "Urban resilience refers to the ability of an urban system - and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales - to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity."

We focus on the dynamics of services and assess persistence and adaptation required for maintaining and recovering the system function after shocks. Following Meerow et al. (2016), the focus of our quantitative analysis is on short-term resilience, while long-term resilience is only discussed together with perspectives on transformation and sustainability.

We assess the resilience of urban water supply services for seven urban case studies located in contrasting hydroclimatic regions and a wide range of socioeconomic conditions. The spatial boundaries of the urban systems include both formal and informal settlements of a metropolitan area or municipality, depending on the case study. Services are aggregated across areas of high and low (or no) services, to reflect the reality of many urban areas worldwide (see Krueger et al., 2019 for details). The model framework of Klammler et al. (2018) is parameterized based on the CPA framework presented in Krueger et al. (2019). Results by the former showed the existence of multiple stable states in the interaction of infrastructure services and adaptive management, as well as contingency of services on stochastic shock regimes. Results of the CPA analysis by the latter authors showed that capital availability and robustness are positively correlated, while risk correlates negatively. In combining the two, our research is guided by the hypotheses that (1) the relationship between urban water security and resilience is nonlinear, with potential for tipping points resulting from an imbalance of capital availability and robustness. If confirmed for urban infrastructure services, the nonlinearity and tipping point behavior found in natural and other coupled complex systems (Lade et al., 2013; Park & Rao, 2014; Scheffer, 2009) would make an interesting comparison. (2) While city-scale total water services can be increased by community adaptation in response to service deficits, this increase varies due to different constraints in community adaptive capacity.

2. Methods

2.1. System Dynamics Model for Urban Water Supply Services

The model describes the temporal dynamics of two coupled system states, *service deficit* ($0 \leq \Delta(t) \leq 1$) representing the deficit of water supply services at the citizen scale and (2) *service management* ($0 \leq M(t) \leq 1$) representing service maintenance and recovery. Service deficit (Δ) and service management (M) are aggregated (averaged) values for the entire system. The equations are derived from models describing the behavior of complex ecological systems and are applied here to complex urban systems. We use the scaled parameters and normalized equations, so that the model is *nondimensional* (normalized to unit replenishment rate in adaptive capacity). The coupled temporal dynamics of these dimensionless state variables is written as (Klammler et al., 2018) follows:

$$\frac{\mathrm{d}\mathit{\Delta}}{\mathrm{d}t} = (1-\Delta)b - a\mathrm{M}\mathit{\Delta} + \xi \tag{1}$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = (1-c_1\Delta)M(1-M) - \mathrm{r}\frac{M^n}{\beta^n + M^n} - c_2\xi \tag{2}$$

where the first term on the right side of equation (1) represents growth in service deficit (Δ = 1-Service/Demand), which is the sum of demand growth and service degradation (rate constant b). The second term in equation (1) represents service recovery provided by M with efficiency coefficient (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). Replenishment in the capacity of service management (M, equation (2)) follows a logistic function and is limited by coupling with Δ through c_1. For $c_1 = > 0$ the two systems are increasingly decoupled. Capacity of M can be lost as a result of insufficient management efficacy and lack of financial capital and can be aggravated by degrading infrastructure and insufficient water resources. The degradation of M follows a Langmuir (or Hill-type) function (Langmuir, 1918), determined by the maximum relative depletion rate (r). The shape of the depletion curve in M is characterized by the scale β at which the degradation of service management begins to level off, and the shape (steepness) n of the degradation curve. Shocks can directly impact M, depending on the value of coupling parameter c_2.

Numerical simulations of time series are generated for the two state variables (Δ and M) by simultaneously solving equations (1) and (2) using a MATLAB ordinary differential equation solver (ode45), applied separately to each time interval between shocks. Shock magnitudes (α) are added to Δ and subtracted from M at the end of each interval to form the initial value for the subsequent interval. Simulations are conducted for 1,000 time units for each system, long enough with respect to mean shock arrival times and recovery time scales, such that states contained in a single realization are representative of average system behavior, and account for memory effects resulting from recurring shock impacts.

Dimensionless time (t) is scaled proportional to unit replenishment rate in service management ($t = t_{\mathrm{real}}\, r_{\mathrm{RF}}$; see (Klammler et al., 2018) for further details on normalization of equations (1) and (2)). This means that t

represents varying lengths of real time, depending on each type of city and the magnitude of shock impacts, and can be in the order of days or weeks (or less for resilient and water secure cities) or months to years (or even decades for nonresilient and transitional cities). While there are no comprehensive long-term empirical data on recovery times in response to different types of chronic and acute shocks in different cities, examples demonstrate that recovery is slower in poorer as compared to richer areas (Cutter & Emrich, 2015; i.e., low versus high capital availability and robustness). A typical example of a chronic shock is supply intermittence due to the bursting of a water distribution pipe. Our data for Amman, Jordan, suggest that recovery from such shocks is in the order of $\leq$1 day. However, recovery from larger, less frequent shocks may take much longer. For example, the 2017 Central Mexico earthquake disconnected 6 million people from the water pipe network. Most services were recovered within around 2 weeks (Audefroy, 2018); however, recovery was an ongoing process 6 months later (Hares, 2018; Unicef, 2018). Recovery from even more severe shocks, such as civil war, is a multiyear process. Liberia's capital Monrovia has faced severe water supply insecurity since the city's hydropower plant—necessary for powering the water treatment plant and distribution system—was destroyed in 1990, at the beginning of the 14-year civil war (Smith et al., 2013). Even since the end of the war, water supply was secured only for 25% of the city's population, with improved prospects since the reconstruction of the hydropower plant in 2016 (FPA, 2016a, 2016b). The total simulated time series of 1,000 time units is therefore in the order of years to decades.

2.2. Capital Portfolio Approach (CPA)

The CPA developed and applied by Krueger et al. (2019) considers (1) public services provided by a municipal entity and (2) total services resulting from a combination of public services and community adaptation in response to insufficient services (additional water bought on the private market, water stored, and treated at the household level, etc.). Public services require four types of capital: water resources (W, "natural capital," including naturally available and captured water resources); infrastructure (I, "physical capital") needed to store, treat, and distribute W; financial capital (F) to build, operate, and maintain the water supply system; and management efficacy (P, "political capital") to operate and maintain services. Community adaptation ("social capital," A) complements or replaces insufficient public services. These capitals are quantified based on performance, rather than based on capacity, and therefore, they measure outcomes that include losses due to inefficiencies. Three dimensions of these capitals are considered: availability, robustness, and risks.

Two aggregate metrics represent capital availability required for public water supply services ($CP_{\text{public}} = \{\text{W, I, F, P}\}$) and total services ($CP_{\text{total}} = (CP_{\text{public}} + \text{A})$), which includes the adaptation and additional "self-services" of the community. Robustness of public and total services ($RP_{\text{public}} = \{W_R, I_R, P_R, F_R\}$ and $RP_{\text{total}} = \{W_R, I_R, P_R, F_{R,} A_R\}$) and acute and chronic risk of shocks represent additional dimensions used for the parameterization of the model. Availability, robustness, and risk are determined for each of the five capitals using scored and aggregated attributes, which are compiled across the five capitals in a hierarchical aggregation procedure using additive and mixed additive and multiplicative aggregation methods (Krueger et al., 2019). An overview of adequate aggregation methods is provided in Langhans et al. (2014). Krueger et al. (2019) pay close attention to aggregation in terms of substitutability or multiplicative effects (e.g., one-out, all-out effects) but refrain from weighting the different metrics and submetrics in the CPA. While certainly expert weighting, such as proposed by several authors (Eakin & Bojórquez-Tapia, 2008; Romero-Lankao & Gnatz, 2016; Vincent, 2007) would provide more nuanced results, keeping the same relative metric weights (unweighted) makes sense for this analysis for several reasons: (1) The specific objective function analyzed here (urban water supply security) aggregated at the city scale is the same across all case studies, and for the objective function to be achieved, the same set of capitals (with submetrics) is required for fully functional services (Krueger et al., 2019). If and how the diverse submetrics interplay in providing services is —to date—unknown. (2) Data availability is highly variable across case studies, and data uncertainty is high. Adding weights to (differentially) uncertain data would complicate and potentially distort the overall picture. Thus, refinement of the analyses for individual cities should be done in a coproduction process with local stakeholders involved in expert judgement for assessment and potential weighting of submetrics. (3) The resilience analysis proposed here serves the purpose of understanding system dynamics and aggregated services as a fraction of total rather than deciphering processes and interactions taking place inside the system. Weighting the different submetrics would be useful for understanding the interplay among the capitals (and submetrics), which is beyond the scope of the research presented here.

As laid out in the CPA, our investigations here explicitly address water supply services in terms of quantity. Water quality is implicitly addressed in several ways: (1) the ability of the public supplier to provide water at safely drinkable quality (based on the need of the community to treat water at the household level—see quantification of I in the CPA approach; (2) the quantification of community adaptation considers the need for treating water to make it drinkable (see quantification of A of the CPA approach); (3) the robustness of water resources considers the governance of water quality in a ranked scoring system; and (4) considered risks include contamination through dilapidated or lack of infrastructure (e.g., epidemic incidences caused by intrusion of sewage), as well as through industrial spills caused by upstream industry. In addition, the CPA implicitly addresses spatial and temporal dimensions. Access (spatial) to water services is considered in the quantification of the state of infrastructure through the household connection rate. The temporal dimension is considered in the continuity of supply through the need for the community to bridge temporal supply gaps (e.g., in rationed supply schedules).

We use these metrics representing the three dimensions of the CPA to reframe the model parameters. Resilience of water supply services is assessed by simulating impact-recovery cycles for the seven case study cities. Below, we refer to capital portfolio (CP), robustness portfolio (RP), and equivalently Δ, M, which can be $[X]_{\text{public}}$ or $[X]_{\text{total}}$, if community adaptation and resilience are added/subtracted accordingly.

2.3. Model Parameterization

Service deficit (Δ) and service management (M) result from the interaction of the four (five) capitals. Service deficit represents the deficit in services at the citizen scale comprising deficits in access, continuity, reliability, affordability, and safety (of water quality and of access). It is the combination of CP and RP that contributes to these aspects of water supply services. Equivalently, the maintenance and recovery of services is marshaled through capital availability and robustness determined by the parameters described below.

Parameter b is the sum of two additive processes: demand growth and service degradation. Capital availability is required for keeping up with demand growth, and capital robustness is required for service maintenance. Therefore, the lack of capital prevents urban managers from keeping up with demand growth, and lack of robustness leads to service degradation. So b is expressed by

$$b = (1 - CP) + (1 - RP) \tag{3}$$

Δ is recovered through M and depending on efficiency coefficient a, which is defined as

$$a = \sum C_i \sum R_i \tag{4}$$

Higher capital availability and robustness result in more efficient recovery of services (robustness for capitals W, I, and F and preparedness to deal with shocks for capitals P and A; for brevity summarized as “robustness”).

Coupling parameter c_1 determines the impact of service deficit on service management. Higher robustness buffers the impact of service deficit on service management. Therefore, when robustness is lacking, the recovery of M is limited

$$c_1 = 1 - RP \tag{5}$$

According to Klammler et al. (2018), parameter r is the ratio of depletion over replenishment rates and corresponds to the maximum depletion rate. Depletion of M is highest, when capitals and robustness are low. Thus, depletion rate r corresponds to average lack of robustness and capitals:

$$r = 1 - (CP + RP)/2 \tag{6}$$

Coupling parameter c_2 indicates the direct impact of shocks on service management. The ability to absorb shocks diminishes with diminishing capital availability and robustness. Therefore, the direct impact of shocks on service management is as follows:

$$c_2 = r = 1-(CP+RP)/2 \tag{7}$$

The scaling constant β signifies the scale at which degradation of M begins to level off.

$$\beta = RP \tag{8}$$

that is, when the level of robustness is reached.

The unitless coefficient n determines the steepness of the switch in service management as M reaches β, where higher n values result in a steeper switch around β, while smaller n values result in a more linear leveling off of service management degradation. n indicates how fast shocks impact M. It is set to

$$n = \sum R_i \tag{9}$$

In the parameterization proposed above key model parameters are strongly correlated and determined by CP and RP. We assume that in urban systems, by definition, CP $\neq 0$.

2.3.1. Disturbance Regime

Various types of chronic and acute shocks impact different urban water systems, depending on a city's sociopolitical, economic, geographic, and climatic environment. Twelve types of threats resulting from four groups of hazards, which have the potential of producing shocks to the urban water supply system, have been proposed by Krueger et al. (2019). Examples of chronic shocks are land subsidence causing infrastructure damage and contamination of piped water, competition for water resources, and illegal tapping into water pipes. Acute shock examples include earthquakes and landslides, industrial spills, war, or drought. A complete list of hazards resulting in chronic and acute shocks is provided as supporting information (*SI*).

The disturbance regime is characterized by the combination of chronic and acute shock time series. The number of shocks follow a Poisson distribution of mean frequency (density) λ $(1/T)$; mean magnitude α $(-)$ is drawn from an exponential distribution, with shock magnitudes relative to demand. Mean frequency of chronic shocks is as follows:

$$\lambda_{\text{chronic}} = \frac{\text{chronic shock score}}{\sum \text{chronic shocks}} \left(1+RP_{\text{public}}\right)^{-1} \tag{10}$$

where the shock score results from the summed binary scores (potential of occurrence = 1, exclusion of occurrence potential = 0) for each risk type divided by the sum of total potential risks. Adjustment by RP_{public} indicates a city's ability to buffer shocks: According to Rodriguez-Iturbe et al. (1999), censoring (buffering) of shocks does not change shock magnitude but results in a lower frequency of shocks. We apply this logic as suggested by Klammler et al. (2018) by censoring shocks proportional to RP_{public}. Acute shock frequencies are assumed to occur an order of magnitude less frequently:

$$\lambda_{\text{acute}} = \frac{\text{acute shock score}}{\sum \text{acute shocks*10}} \left(1+RP_{\text{public}}\right)^{-1} \tag{11}$$

Combined risks resulting from various causes can lead to supply intermittence or other disruptions in water services. Cities prepare for chronic shocks by installing isolation valves in the distribution networks to limit the affected population (Ozger & Mays, 2004). In case of a lack of adequate isolation valves within the network, the entire distribution zones can be affected (Zischg et al., 2019). Distribution zone size depends on topography, network design, and operational strategies, and the cases investigated here are in the order of 2–3% of the population (Abu Amra et al., 2011; CONAGUA, 2016). Acute shocks can affect large parts of the population. For example, the 2017 Central Mexico earthquakes left 25% of the population without water (Audefroy, 2018) and the 2003/2004 drought in Chennai, affected around 65% of the population (Srinivasan, 2008). Thus, we used mean magnitudes $\alpha_{\text{chronic}} = 0.03$ for chronic and $\alpha_{\text{acute}} = 0.2$ for acute shocks.

We assessed the mean and maximum affected population based on actual isolation zones using isolation valve data for three cities. For Amman (data courtesy of Miyahuna Jordan Water Company), mean affected population (based on demand) was between 0.3% and 1.0%, while maximum affected population was between 6% and 38% for six distribution zones. Data analyzed for Ottawa, Canada (Jun, 2005), and

Innsbruck, Austria, indicated maximum affected population of less than 1%. Differences between $\alpha_{\mathrm{chronic}}$ and the stated values for affected population by isolation zones indicate the buffering capacity of different city types, which manifests in our model as a reduction in mean shock frequency (see equations (10) and (11)).

Shock regimes are produced stochastically as the sum of time series of chronic and acute shocks, respectively, representing realistic scenarios of disturbances impacting water supply services. Shocks are added (subtracted) to service deficit and service management in each time step (see equations (1) and (2)).

2.4. Case Studies

We assess the resilience of urban water supply systems in seven cities on four continents. Cities were selected based on their contrasting water systems, which result from differences in capital availability, and lead to variability in water supply security. Three cities have fully developed capital portfolios and high levels of water security: Melbourne (Australia), Berlin (Germany), and Singapore. Following a drought that lasted more than a decade, Melbourne developed water infrastructure (large reservoir storage and desalination plants) that provides excess capacity during normal years and is maintained at high financial cost (Ferguson et al., 2014). Berlin maintains availability of some excess water resources, which is a result of a decline in industrial production following the German reunification and reduced domestic demand due to demand management measures (Moeller & Burgschweiger, 2008). Singapore maintains sufficient resources in a delicate balance of natural availability, water recycling, and water imports (Lee, 2005; Public Utilities Board, 2017; Ziegler et al., 2014).

Two cities have intermediate levels of CP: Amman (Jordan) and Mexico City (Mexico). Amman represents a city in transition aspiring water security, in spite of the country's water scarcity (water availability $<150\ \mathrm{m}^3\cdot\mathrm{cap}^{-1}\cdot\mathrm{year}^{-1}$). Urban water security is a key priority in this arid country (MWI, 2015). Large-scale investments (International Resources Group, 2013) and international agreements on transboundary water transfers (Klassert et al., 2015; Rosenberg et al., 2008) and continued support from international organizations and donors have allowed connecting close to 100% of the urban population to the piped network (Bonn, 2013; Rosenberg et al., 2007). Community adaptation mainly is a response to rationed water supply, forcing citizens to store water in rooftop tanks to bridge supply gaps during water supply intermittence (Rosenberg et al., 2007). High water abundance and low availability of all other capitals in Mexico City result in a transition water system that is characterized by the degradation of large-scale, inflexible water infrastructure and water managers overwhelmed by ceaseless population growth and large, frequent disruptions such as earthquakes (Lankao & Parsons, 2010; Tellman et al., 2018) with diverse strategies of community adaptation, including rooftop storage and access to private water vendors (Eakin et al., 2016).

Two cities have low CP: Chennai (India), where the lack of capitals for public services (CP_{public}) is only balanced by community adaptation (A) including self-supply from private wells and the private water market (Srinivasan et al., 2010). In Ulaanbaatar (Mongolia) deficits of all five capitals result in desperately low levels of services (Gawel et al., 2013; Myagmarsuren et al., 2015). Large inequality of water services in Ulaanbaatar is reflected in the operation of a split water system. The modern, central apartment areas receive piped warm and cold water at the household level, while around 60% of citizens live in the sprawling Ger areas (settlements lacking adequate infrastructure services) without access to piped water supply, sanitation, or roads. Ger residents have an average per capita water use of 8 liters per capita and day (lpcd), which they collect from water kiosks (Myagmarsuren et al., 2015). Frequent service interruptions due to frozen pipes are not uncommon, with temperatures as low as −40 °Celsius. Ger residents drill shallow wells to access water directly on their property and open-pit latrines substitute as sanitary infrastructure, which threatens the safety of the city's water sources (Myagmarsuren et al., 2015).

Cities faced with water service deficits often ration supply schedules, requiring citizens to store and treat water at the household level and to supplement supplies through private services (Eakin et al., 2016; Klassert et al., 2015; Potter et al., 2010; Srinivasan et al., 2010). Intermittent supply through leaking pipes and dependence on shallow wells in proximity to dug latrines are significant water quality concerns (Gerlach & Franceys, 2009; Roozbahani et al., 2013; Sigel et al., 2012). Reliance on water sharing among households is yet another coping/adaptation strategy among households in poorer districts (Potter et al., 2010).

CPA data for the seven cities are provided in the SI. For details of the CPA analysis and more complete descriptions of these seven cities, see Krueger et al., 2019.

3. Results

The model parameter input values resulting from the translation of the CPA for each of the seven cities are shown in Table 1a. We use one or two parameterizations for each city: one for public services only, where public services do not meet demand, and one for total services, which includes community adaptation of private households. In Ulaanbaatar, we also separately assess apartment (UB Apart) and Ger (UB Ger) areas in order to reveal the large inequality underlying the city's average service levels.

The model is solved for the following variables: (1) fixed points of M and Δ (M_{fix} and Δ_{fix}), which are stable points for public and total service deficit in each case study, respectively. Stable points are system attractors, toward which systems converge in the absence of shocks. (2) Mean values (μ) and the coefficient of variation (CV) of M and Δ over the entire time series. (3) Crossing times (CT) are mean crossing times below and above a threshold defined by the expected mean values ($M_{\mathrm{thresh}} = M_{\mathrm{fix}} - c_2{}^{*}\, \alpha_{\mathrm{chronic}}$; $\Delta_{\mathrm{thresh}} = \Delta_{\mathrm{fix}} + \alpha_{\mathrm{chronic}}$), which are a measure of the rapidity of service recovery after shocks. Numerical model results are presented in Table 1b, as well as in Figure 2 (additional figures are presented in the SI).

For cities with a chronic deficit in water services, community adaptation significantly increases urban water services, so that total services are much larger than public services. Due to the impacts of the shock regimes in all but the first three cities, mean values are significantly lower and higher than fixed points M_{fix} and Δ_{fix}, respectively. Mean, CT and CV are relatively low (see results for each city below). While higher values might be expected, the implementation of urban infrastructure serves the objective of reducing natural variability, which explains the relatively low variability of services compared to unmanaged systems, such as river discharge. $CT_{\Delta\mathrm{above}} < CT_{M\mathrm{below}}$ indicates that services are recovered faster than service management. CV_{Δ} increases with increasing services as a result of decreasing mean service deficit ($\mu_{\ \Delta}$).

The dynamic behavior of each system is contingent on the specific (stochastic) shock regime. We tested the probability of failure in response to shocks using a Monte Carlo approach, by running 1,000 simulations × 1,000 time units for each model parameterization. "Collapse" or "failure" of the system refers to the breakdown of services (public and/or total), for which the condition is $\Delta(t) = 1$ and $M(t) = 0$. The simulations terminate in the case of collapse. However, depending on the severity of the damage, the availability of support for reorganization and recovery, systems tend to be recovered after some lag time (see example for Chennai public services).

Results of failure probability simulations are shown in the last row of Table 1b ., as well as in Figure 1. We plot the timing of collapse for all 1,000 simulations in Figure 1. While failure probability is high for multiple case studies, the "survival length" (time to collapse) is contingent on the realization of the shock regime. Outcomes of t_{collapse} are highly variable across *and* within cities (compare UB Apart and UB Ger), varying over 3 orders of magnitude.

Based on the CPA assessment and model results, we present in the following three broad groups of cities. While there are no sharp boundaries between the groups and cities that fall along a continuous gradient from low to high security and resilience, we use these broad categories for the convenience of organizing the presentation of results. (1) Water secure and resilient cities completely recover after shocks in all simulation runs, (2) water insecure and nonresilient cities have a probability of failure ≈100%, and (3) cities in transition have a failure probability significantly less than 100%. Over time, cities in transition have managed to increase service security and resilience to a degree that mostly allows recovery from shocks, thereby escaping the poverty trap. They may also have transitioned into this "middle position" as a result of service decline (e.g., through high population growth and infrastructure degradation), where the inability to maintain high levels of security has led to a loss of services over time. In section 3.4 we show the simulation of the entire realistic parameter space. It indicates that cities could transition into an area of multiple stable states, such that nonlinear system evolution is reasonably possible with the potential of crossing tipping points and loosing service security despite high capital availability.

Table 1a
Input Parameters of System Dynamics Model

		Melbourne	Berlin	Singapore	Amman	Mexico City	Chennai	Ulaanbaatar	UB apart	UB Ger	Amman	Mexico City	Chennai	Ulaanbaatar	UB apart	UB Ger
		Public services									Total services					
Model parameters	r	−0.09 (0.01[a])	0.06	0.12	0.48	0.58	0.69	0.64	0.51	0.77	0.26	0.38	0.34	0.51	0.45	0.55
	b	−0.18 (0[a])	0.12	0.24	0.96	1.15	1.38	1.28	1.03	1.54	0.53	0.77	0.67	1.01	0.91	1.11
	n	3.75	3.36	3.37	2.13	1.88	1.46	1.8	1.8	1.8	2.84	2.59	2.17	2.09	2.23	2.09
	β	0.94	0.84	0.84	0.53	0.47	0.36	0.45	0.45	0.45	0.71	0.65	0.54	0.52	0.56	0.52
	a	23.68	13.97	12.77	4.99	4.10	1.70	2.28	5.18	0.59	7.37	6.2	3.69	3.05	6.68	1.43
	c_1	0.06	0.16	0.16	0.47	0.53	0.64	0.55	0.55	0.55	0.29	0.35	0.46	0.48	0.44	0.48
	c_2	−0.09 (0[a])	0.06	0.12	0.48	0.58	0.69	0.64	0.51	0.77	0.26	0.38	0.34	0.51	0.45	0.55
	$\lambda_{chronic}$	0	0.09	0.09	0.44	0.57	0.61	0.46	0.46	0.46	shocks same as for public services					
	λ_{acute}	0.02	0.01	0.02	0.03	0.05	0.05	0.05	0.05	0.05						

[a] Adjusted negative rate parameters r and b and values for shock impacts (c_2).

Table 1b .
Numerical Results for Urban Case Studies

		Melbourne	Berlin	Singapore	Amman	Mexico City	Chennai	Ulaanbaatar	UB apart	UB Ger	Amman	Mexico City	Chennai	Ulaanbaatar	UB apart	UB Ger
		Public services									Total services					
Numerical solutions	M_{fix}	0.99	0.96	0.92	0.48	0.25	0.01	0.19	0.29	0.08	0.81	0.69	0.65	0.4	0.56	0.31
	Δ_{fix}	0	0.01	0.02	0.28	0.53	0.99	0.75	0.4	0.97	0.08	0.15	0.22	0.45	0.20	0.71
	μ_M	0.99	0.96	0.92	0.46	0.17	—	0.14	0.24	0.07	0.80	0.67	0.63	0.36	0.54	0.28
	μ_Δ	0	0.01	0.02	0.30	0.65	—	0.81	0.47	0.98	0.09	0.16	0.23	0.49	0.21	0.75
	CV_M (%)	0	0.13	0.42	5.80	34.42	—	29.20	20.86	13.85	1.22	3.02	4.71	14.33	6.18	9.68
	CV_Δ (%)	∞	60.82	45.62	9.12	15.31	—	7.06	0.27	0.78	16.13	13.12	14.76	4.26	15.12	4.43
	$\mathrm{CT}_{M\mathrm{below}}$	0	0.90	0.90	1.16	1.62	—	1.46	1.46	—	1.16	1.62	1.68	1.46	1.46	1.46
	$\mathrm{CT}_{\Delta\mathrm{above}}$	0	0.04	0.05	0.19	0.32	—	0.44	0.26	—	0.10	0.13	0.22	0.30	0.14	0.45
	% failure	0	0	0	26.7	100	100	100	97.2	100	0	0.8	1.0	64.5	9.1	95.1

Note. CV = coefficient of variation; CT = mean crossing time.

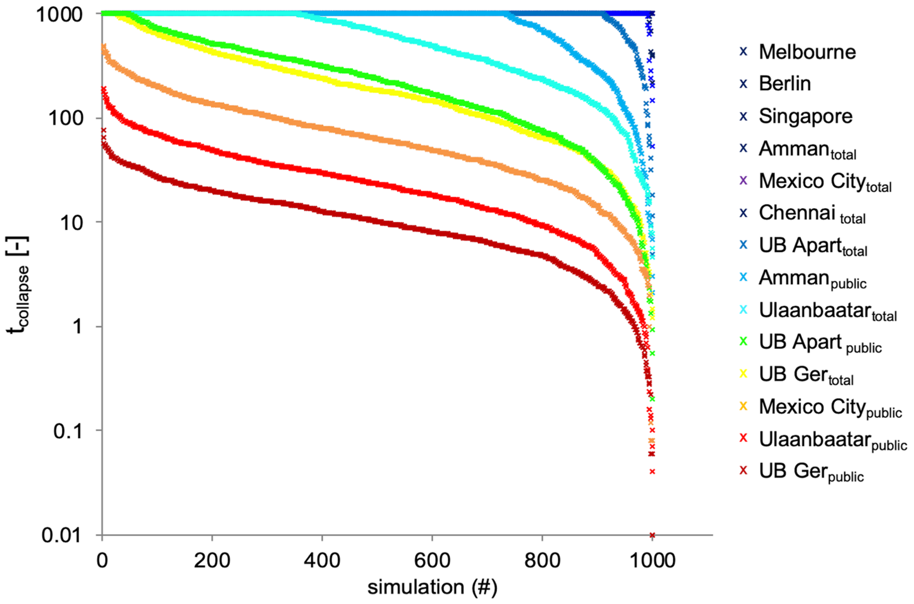

Figure 1. Time of collapse (in scaled time) for 1,000 simulations for all case studies representing different realizations of stochastic shock regimes. No collapse was observed for Melbourne, Berlin, Singapore, and Amman$_{\text{total}}$ (compare to Table 1b .)

3.1. Water Secure and Resilient Cities

In this category, urban managers have reduced risks threatening their water security, so that both chronic and acute shocks occur at low frequencies (see Table 1a). Since the three cities represented here (Melbourne, Berlin, and Singapore) also face relatively low rates of population growth, they are able to keep pace with demand growth and infrastructure degradation (small values of b). Potential shocks impacting services can be efficiently recovered thanks to high availability of capitals as well as system robustness (high efficiency coefficient a). Various factors, including high income levels of citizens, reliable accounting of water services, and anticipatory infrastructure maintenance (see case study descriptions in Krueger et al., 2019), keep depletion of service management low (rate constant r). System robustness in these cities leads to slow depletion of service management (large values for parameters n and β).

Figures 2a–2c**)** show results for Melbourne, representative of water secure and resilient cities. Low magnitude, chronic shocks have been eliminated, causing no increase in Δ nor depletion of M. Acute shocks also have no impact on M. Even a large magnitude event occurring at time step 935 causes no impact on M, as the two systems, Δ and M, are decoupled (coupling parameters c_1, $c_2 \approx 0$). Acute shocks impacting Δ are so quickly recovered that residents are unlikely to notice the deficit ($t \approx$ days or less). The decoupling between Δ and M indicates that urban managers have access to large amounts of capitals, and robustness is high, so that any shock impacting their water systems can be buffered or quickly recovered without any impact on the ability of the managers to deal with recurring shocks. The degree of decoupling increases from Singapore, to Berlin, to Melbourne (decreasing values of c_1 and c_2; see Table 1a).

The state-phase diagram (Figure 2c) shows a single stable state with $\Delta \approx 0$ (no service deficit, i.e., full services) and $M \approx 1$ (maximum service management capacity). The horizontal phase lines and the M-nullcline (horizontal at $M = 1$) indicate that any magnitude event will only impact services, with response decoupled from M. Thus, under the assumption of static CP and RP, this type of city would always recover to a state with full services, even when faced with large shocks. In the case at hand, a 13-year drought hits Melbourne over the years 1997–2010, and urban managers invested in various infrastructure, including additional storage reservoirs, desalination plants, as well as adapting its governance system to be more responsive to droughts before critical reservoir level thresholds were crossed (Ferguson et al., 2013). Thus, it did indeed buffer the drought and recover from the deficit in its reservoirs. Similarly, Singapore has (limited) buffer capacities for desalinating water when precipitation levels are insufficient to replenish the city's storage reservoirs

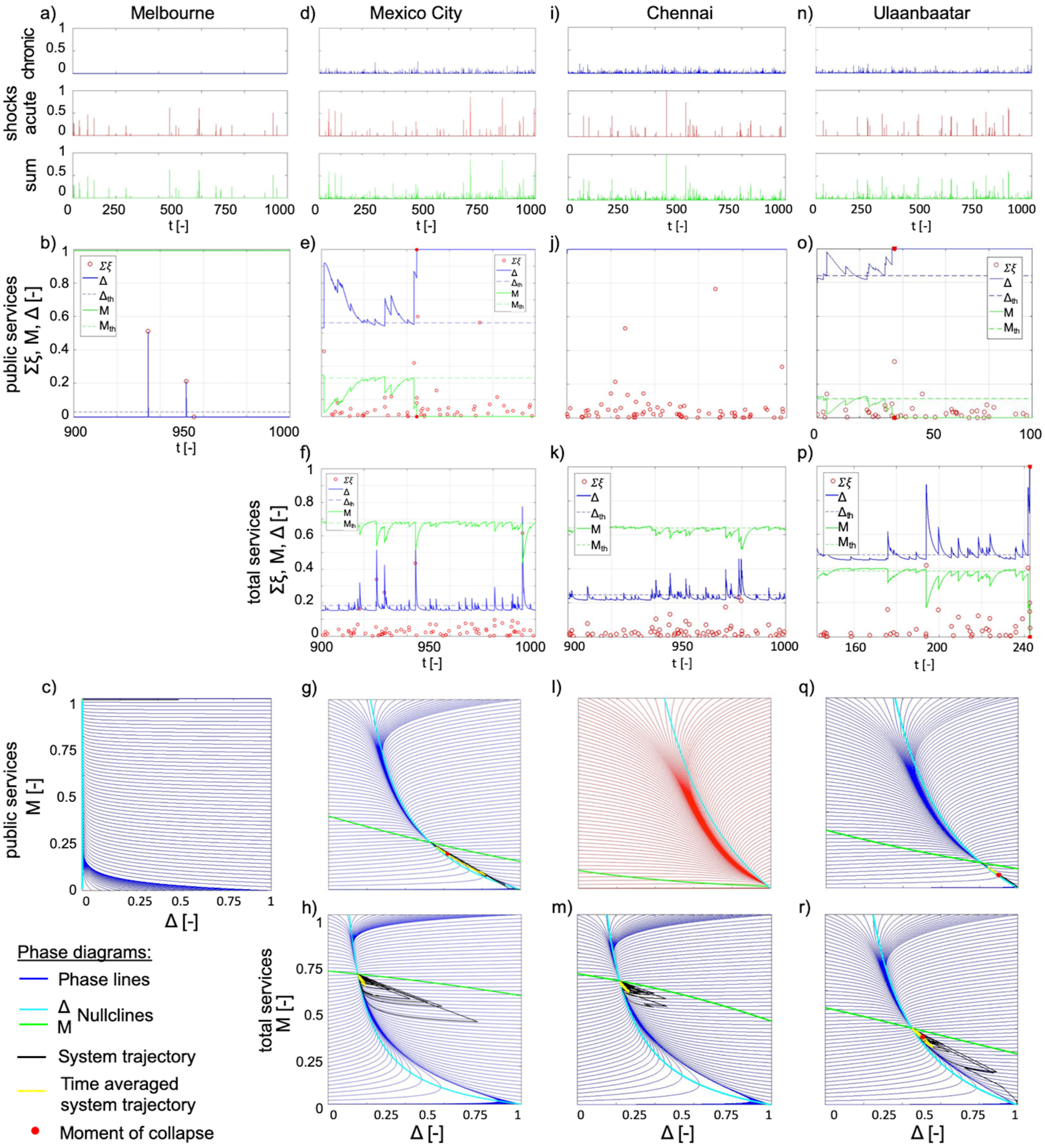

Figure 2. Time series and phase diagrams for different types of cities. Top panels: Time series of shocks ($T = 1{,}000$) with chronic (top row), acute (middle row), and combined shock regimes (bottom row). Center panels (rows 2 and 3): Time series of ξ, Δ, and M and phase diagrams show trajectories for the last 100 time unit window, only, in order to better illustrate individual shock impact and recovery processes. Lower panels (rows 4 and 5): State-phase diagrams serve to identify stable states by running 100 model iterations for the phase trajectories (blue lines) to converge. Undisturbed phase trajectories (blue) converge toward a single stable point (intersection of Δ and M nullclines). System trajectories including shocks (black lines) correspond to time series of Δ and M. Yellow trajectories are time averaged; red dot marks moment of collapse on time-averaged trajectory. (a–c) Results for Melbourne as an example of resilient and water secure cities. (d–h) Mexico City representing cities in transition. Shocks lead to system collapse of public services. (g, h) Phase diagrams illustrate the increase in water security and resilience achieved through community adaptation compared to public services, only. (i–r) Chennai and Ulaanbaatar illustrate system behavior for water insecure and nonresilient cities. Red phase lines for public services in Chennai (l) indicate convergence toward collapse in the absence of shocks (continuous degradation of services). Shocks lead to system collapse in Ulaanbaatar (o–r). Comparison of phase diagrams of public services (j, o and l, q) with total services (k, p and m, r) illustrates the regime change from low security and resilience toward an intermediate state, which is achieved through community adaptation. Time series for public services in Chennai are not produced (except shocks), as collapse occurs even in the absence of shocks (red phase lines). In the case of collapse ($T < 1{,}000$), the last 100 time units before collapse are shown (o, p)

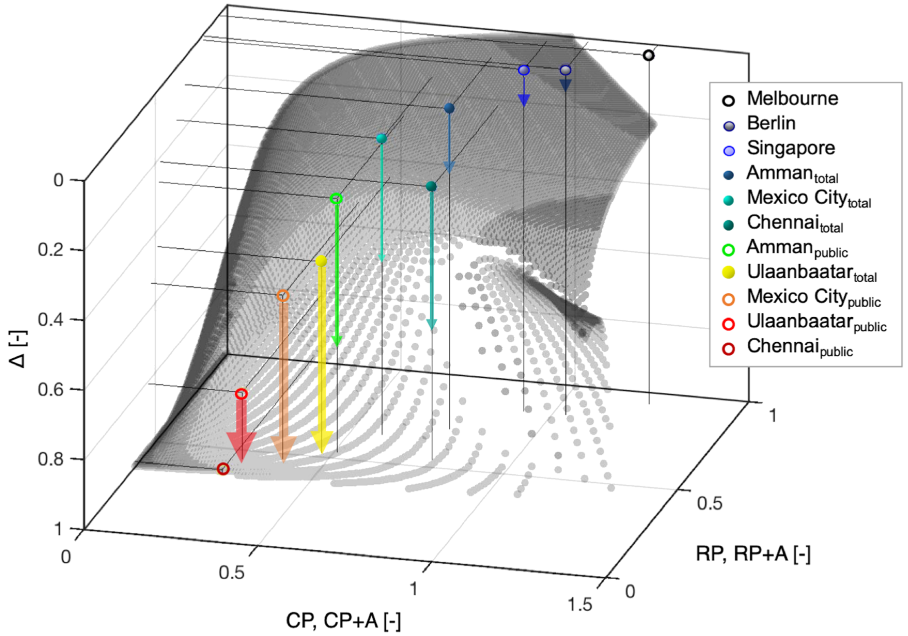

Figure 3. Resilience landscape simulated from systematic parameter variation across the entire parameter space and case study cities. Melbourne case study is positioned outside of the resilience landscape, because the model does not allow negative parameters, and we use adjusted parameters to calculate results for Δ (see Table 1a). **a* was calculated as $a = (\mathrm{RP} * 4) * (\mathrm{CP} * 4)$. CP = capital portfolio; RP = robustness portfolio

(Ziegler et al., 2014). These results show dynamic behavior under current conditions but do not make predictions or produce future scenarios, for which changing conditions (e.g., in RP) could be assumed. Such changes could produce multiple stable states, as illustrated in Figure 3. See section 4 for further discussion.

3.2. Water Insecure and NonResilient Cities

In Ulaanbaatar (Mongolia) and Chennai (India) public water services cover only a fraction of demand due to a combination of water scarcity (economic or physical), lack of or decrepit infrastructure, as well as limited management capacity and rising demand due to population growth. The community adapts to insufficient services through various strategies, such as drilling private water wells, buying water on the private market (e.g., tanker trucks, stores), or using public facilities for laundry washing and personal hygiene, such as in public bath houses, or sharing water among neighbors (Myagmarsuren et al., 2015; Rosenberg et al., 2007; Sigel et al., 2012; Srinivasan et al., 2010).

Figures 2i–2r) summarize the results for these two cities. Shocks occur frequently with both low and high magnitude (Figures 2i and 2n), and they lead to collapse of both public and total services in Ulaanbaatar, as indicated by the red dots marking the moment of collapse in the time series in Figures 2o and 2p. Public services in Chennai are characterized by low CP and RP, and the city's water system thus converges toward collapse even in the absence of shocks, which is illustrated by the phase diagram in Figure 2l), where red phase lines direct the system toward $\Delta \approx 1$ (no water services) and $M \approx 0$ (no capacity for service management); thus, a time series of shocks and recovery is not shown. In 2003/2004 a drought led to the complete suspension of piped water services (Srinivasan et al., 2013). However, the phase diagram for Chennai demonstrates that even in the absence of such shocks, population growth and increasing demand for water resources or competition among urban, periurban, and agricultural sectors would ultimately lead the urban water system into collapse without additional investment into water security. This finding is supported by the recent drought (2019), which has once more led to the suspension of piped water supply. Although public services in Ulaanbaatar are characterized by similarly low capital availability, slightly higher levels of robustness ($RP_{\mathrm{public}} = 0.45$ in Ulaanbaatar versus 0.36 in Chennai) keep the system just above collapse for the equilibrium solution (higher system robustness for Ulaanbaatar determines the dynamics of service management, Figure 2q), compared to no dynamics in Chennai Figure 2l).

Public services in these cities are indicative of a poverty trap, where inability to marshal the necessary capitals keeps systems precariously close to collapse (failure probability assessed in the Monte Carlo simulation ≈ 100%; see Table 1b . and Figure 1). Community adaptation changes these cities' water security into a transitional state (Figures 2m and 2r). The high adaptive capacity of Chennai's community (Srinivasan et al., 2013) leads to system resilience of total services, with recovery to relatively high levels of total services even from large shocks. Two consecutive large shocks to total services around $t = 980$ (Figure 2k) or after around 80 years for unit $t \approx 1$ month represents an event such as the 2003/2004 drought, which the urban community was able to cope with through adaptive measures. Given the recent drought episode, we suggest that the quantification of A in the CPA for Chennai was overestimated (see section 4.). For total services in Ulaanbaatar, large values of c_2 lead to a strong impact of shocks on service management, which is why recovery is not possible from large and recurring shocks, and system collapse occurs at $t = 243$ or after around 60 years for unit $t \approx 2–3$ months (Figure 2p). This response is aggravated due to nonlinearity in the system model: for higher levels of Δ and M phase lines are horizontal, indicating that Δ is recovered first, before the recovery of M (area between two nullclines in lower right-hand corner of Figure 2r) and closer to the green M-nullcline). The direction of the phase lines changes the closer the system moves toward the light blue Δ-nullcline, indicating that here service management is recovered first, as it is required to usher service deficit recovery. Where recovery from shocks is possible, a time lag resulting from strong coupling of service management to service deficit (large values of c_1), as well as low efficiency in recovery (low values of a), can be observed for both Ulaanbaatar and Chennai (Figures 2k and 2p). This contrasts with the immediate recovery for the resilient and water secure cities. Ulaanbaatar survived a shock at $t = 195$ (after around 50 years), while a shock of the same magnitude at $t = 243$ leads to collapse, because the system had not fully recovered from a shock that had occurred shortly before ($t = 241$). This demonstrates the contingency of these urban water trajectories on specific shock scenarios.

Results for separate model runs for Ulaanbaatar's split water system for Ger and apartment areas for public and total services indicate that public services in Ger areas would not function without community adaptation, as residents are required to fetch their daily water needs from kiosks (Sigel et al., 2012; see results in Table 1b .); figures and data used for model parameterization are provided in the SI. Total services in Ger areas remain highly vulnerable, and recurring shocks make these services prone to collapse, in spite of improved community resilience (Figure 1). Comparison of results between public services in Ulaanbaatar's Ger areas and public services in Chennai shows that in both cases service deficit is $\Delta_{\text{public}} \approx 100\%$. However, high capacity of Chennai's citizens to adapt to the highly deficient services results in a total service deficit of only $\mu_{\Delta\text{total}} = .23$, while it remains at $\mu_{\Delta\text{total}} = 0.75$ in UB Ger (Table 1b .).

Although apartment areas in Ulaanbaatar supposedly receive water continuously, we found that public services in these areas have an average deficit of around 40% without community adaptation and around 20% with adaptation. Public service deficit results from low capacity of service management and can lead to collapse in response to recurring shocks due to slow recovery of services. High leakage rates are the result of a degraded distribution network in the central urban area, which dates back to the 1960s and has not received any significant maintenance or replacement.

3.3. Cities in Transition

Capital availability for public services is significantly higher in Mexico City and Amman than in the nonresilient cities presented in section 3.2 (see Table 1). In Mexico City, the combination of relatively frequent chronic and acute shocks, degraded system robustness (resulting in large values of c_2), which leads to significant impact on service management in response to shocks, as well as slow recovery after shocks due to strong coupling of Δ and M (large value of c_1) can cause public services to collapse (see Figures 2e and 2g). Two large shocks occurring around $t = 945$ and $t = 995$ (or after approximately 80 years for unit $t \approx 1$ month) represent events, such as the September 2017 earthquakes. In Amman, all model parameters take intermediate values that describe this transitional status, including a reduction in the occurrence of shocks compared to the water insecure and nonresilient cities. Model results for service deficit in Amman are higher than observed values of public water supply, which covers around 76% of household demand in Amman (Krueger et al., 2019). However, this water is supplied on a rationed schedule with water delivered on

2.5 days per week on average, reducing the level of service, and disturbances are frequent due to pipe bursts, in particular in house connections (data with courtesy of Miyahuna Jordan Water Company). The shock regime reflects the fact that shutting off or rescheduling delivery days becomes necessary for repairs and maintenance work, and network properties designed for continuous supply cause pressure variation within the pipe network. Amman's citizens access an additional 8–10% of their water demand from the private market (Klassert, pers. comm.) and have adapted to rationed water supply by storing water in rooftop and basement tanks. This increases total water services to around 80% (or 20% deficit) on average (see results in Table 1b . and additional text and figures in the SI).

3.4. Resilience Landscape

To better understand the resilient behavior of urban water systems, we tested the entire parameter space by systematically varying CP and RP within the realistic range ($0 \leq \mathrm{CP} \leq 1.4$; $0 \leq \mathrm{RP} \leq 1$), which produces dependent changes to b, r, β, c_1, c_2, a^*, and n. We show service deficit as a function of CP and RP in Figure 3**.** Each point in Figure 3 represents a fixed point. This three-dimensional surface represents a resilience landscape, as it shows all fixed points for the entire parameter space and indicates areas with possible bifurcation or regime shifts. Multiple fixed points appear in the parameter range $CP > 1$ and $RP < 0.3$. This parameter range represents systems with excess capital availability and degraded robustness. Here, cities maintain excess capital at high cost in order to maintain security but risk shifting into an alternate regime if robustness degrades below a threshold of $RP < 0.3$. Such a situation can be considered a rigidity trap (see section 4). While fixed points occur for the entire range of capital values (CP), no fixed points exist for $RP < 0.3$, as long as $\mathrm{CP} < 1$.

Colored circles and dots in Figure 3 represent the case studies with public and total services, respectively. Arrows indicate shock impacts: Arrow length represents maximum impact magnitude on M 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 specified threshold ($CT_{\Delta \mathrm{above}}$; threshold = expected mean service deficit) and is a measure of the rapidity of service recovery after shocks. Cities are distributed within a confined area and along a gradient of decreasing service deficit and increasing CP and RP resulting from the coevolution of infrastructure and institutions (Padowski et al., 2016). Resilience, as indicated by the arrows, increases accordingly, with lower shock impacts and time to recovery with increasing CP and RP.

Visual inspection of Figure 3 shows that CP, RP, and resilience (indicated by the length and width of the arrows) are all positively related in the investigated cities and follow a somewhat linear trend (data correlation shown in SI). However, the fold in the resilience landscape for excess capital availability ($CP > 1$) and low robustness ($RP < 0.3$) demonstrates that the evolution of CP and RP can follow a nonlinear path and bears the risk of systems crossing a tipping point. We propose that systems in a state of ($CP > 1$) and decreasing RP enter into a rigid regime. In this regime, security and resilience no longer coevolve and approach a tipping point that marks the boundary between high and low services (or collapse). This supports our first hypothesis on nonlinearity and tipping points on a theoretical basis (although none of the case studies fall within this area), which we discuss in section 4.2.

In addition, we investigated changes in CP and RP (representative of urban water supply security), as well as $(1 - \mathrm{CT})$ as a proxy for the resilience of public versus total services. As can be seen from Table 2, the increase in these metrics (both absolute and relative) as a result of community adaptation is highly variable, which supports our second hypothesis. For example in Amman, the increases in resilience $[(1 - \mathrm{CT}) + \mathrm{A}]$ due to community adaptation is small (9% absolute and 12% relative) compared to increases in security ($\mathrm{CP} + \mathrm{A} = 25\%$ and 50%, $\mathrm{RP} + \mathrm{A}$ 18% and 34% absolute and relative, respectively). In comparison, the increase in resilience is higher in Ulaanbaatar (14% absolute and 26% relative) compared to increases in security ($\mathrm{CP} + \mathrm{A} = 20\%$ and 73%, $\mathrm{RP} + \mathrm{A} = 7\%$ and $\mathrm{RP} + \mathrm{A} = 16\%$ absolute and relative, respectively). These findings are an indicator of the interplay of drivers of adaptation (chronic and acute service deficits) and constraints (capacity to adapt to a partial “self-service regime” versus coping for survival).

4. Discussion

Increasing pressures from global change have launched a discussion about the adequacy of current water governance paradigms that seek to achieve or maintain water security by focusing on increasing supplies

Table 2
Effect of Community Adaptation on the Security and Resilience of Urban Water Supply Services (Increases for Total Services Due to Community Adaptation in Comparison to Public Services)

City	Value (public services)			Absolute increase (%)			Relative increase (%)		
	CP	RP	(1 − CT)	CP + A	RP + A	(1 − CT) + A	CP + A	RP + A	(1 − CT) +A
Amman	0.51	0.53	0.81	25.28	18.00	9.48	49.57	33.96	11.71
Mexico City	0.38	0.47	0.68	20.52	18.00	19.57	54.00	38.30	28.88
Chennai	0.25	0.36	0.00	53.44	18.00	78.46	213.78	50.00	NA
Ulaanbaatar	0.27	0.45	0.56	19.75	7.00	14.41	73.14	15.56	25.83

Note. CP = capital portfolio; RP = robustness portfolio; CT = crossing time.

and managing water systems through command and control (Eakin et al., 2014; Kirchhoff et al., 2016; Larsen et al., 2016; Marlow et al., 2013; Varady et al., 2016). While the recent scholarship is strongly advocating new paradigms that embrace resilience thinking, promote adaptive capacity, and favor more flexible, modular, and sustainable strategies (Elmqvist et al., 2018, 2019; McPhearson et al., 2016; Meerow et al., 2016; Spiller et al., 2015; Webb et al., 2017), legacy effects of existing systems and slow uptake of such solutions explain why most urban water supply systems are still designed using conventional engineering solutions (Anderies et al., 2013; Marlow et al., 2013).

4.1. Along the Urban Water Security and Resilience Gradient

Here we show that under current conditions and governance paradigms, cities seeking to reliably provide water supply services are still able to codevelop the security and resilience of their water systems. Therefore, although the system dynamics model used here has been shown to produce multiple stable states as expected for complex adaptive systems (Klammler et al., 2018), perhaps surprisingly, all represented urban case studies resulted in a single stable state (and collapse). Shocks and slow recovery can push systems away from their stable states even for extended periods of time. However, given the critical role of urban water services for the functioning of cities, our model results indicate that under current conditions, recovery is likely to the maximum stable state achievable given availability and robustness of capitals. Thus, cities fall along a continuous gradient on the urban water security and resilience landscape from water insecure and nonresilient to secure and resilient systems. Along this gradient, cities are distinguished according to their level of services and their response to shocks. We propose that, as cities grow and invest into their water supply systems, they evolve from water insecure and nonresilient to secure and resilient systems. Movement along such trajectories can occur as a transition from low to high security and resilience and declining in the opposite direction. However, as we discuss in section 4.2, trade-offs can occur between the development of excess capital and the loss of robustness and lead to different (nonlinear) trajectories that deviate from this path.

Water insecure and nonresilient cities have low availability of capitals ($CP_{\text{public}} \lesssim 0.3$), leaving the majority of the population without adequate public services, and citizens are forced to turn to alternate services. Recovery from shocks is slow, and recurring shocks can quickly push such systems into collapse due to lack of robustness (here: Ulaanbaatar and Chennai). Increasing levels of CP and RP result in higher levels of services, but while in a transitional state (here: Amman and Mexico City), some level of service deficit remains and shocks continue to impact supply, requiring adaptive responses by the community.

The combined variability of public water services and community adaptive capacity results in large inequalities of total water services across cities, as well as within cities, and forces some communities to live with high service deficits. We showed that community adaptation is highly variable and constrained by, among others, the availability and access to alternative services. Adaptation is also subject to nonlinear relationships of CP, RP, and (1 − CP). Place-based context provides insights into the meaning of quantitative values:

In Ulaanbaatar's Ger areas, harsh environmental and economic conditions limit community adaptation. In contrast, access to shallow groundwater through private wells and a private tanker market in Chennai allowed the community to practically replace public services to cover its demand. Chennai's water system was able to absorb and recover the shock of the 2003/2004 drought thanks to the strong adaptive capacity of the community (Srinivasan, 2008). However, the recurrence of this type of shock in recent months indicates that community adaptation is limited in its ability to adapt in the event of recurring acute shocks

(Jamwal, 2019; Subramanian, 2019). Since the 2003/2004 drought, deepening groundwater levels and limited access to diminishing water resources delivered from periurban areas by tanker trucks have reduced the capacity of the community to adapt to another high magnitude shock. Quantification of Chennai's capital portfolio used data that included capital availability and robustness measures derived from community adaptation during the 2003/2004 drought. We propose here that parameters were therefore overestimated: community adaptation can increase water security and resilience in response to chronic shocks and improve system performance for single, acute shocks. However, a combination of recurring acute and chronic shocks lead to a degradation of both public and total water supply services.

Relatively reliable service management levels in Amman allow recovery from chronic and acute disturbances in spite of water scarcity. A high level of community adaptation to chronic disturbances (intermittence due to rationed supply schedules and frequent pipe bursts) improves continuity and reliability, rather than increasing volumetric water supply. Relatively low service management levels in Mexico City can result in collapse of public services in response to shocks. The history of Mexico City's urban water evolution demonstrates the legacy effect of decisions taken today or in the past on the long-term urban water trajectories, which can determine the evolution of entire cities (Bell & Hofmann, 2017; Marlow et al., 2013; Tellman et al., 2018).

Besides the reliance on private services, partly or in whole, such as in Amman, Chennai, Mexico City, and Ulaanbaatar, hybrid systems (e.g., piped and trucked) also exist: Chennai's public utility hired private tanker trucks to deliver water bought from farmers' wells during the 2003/2004 drought (Ruet et al., 2007). Similarly, during the 2008 drought in Cyprus, water was delivered by tanker ships from mainland Greece (EEA, 2009), and in Legler (USA) water was delivered to citizens by truck after severe water contamination from a neighboring dump site (Edelstein, 2004, p. 55). However, although the structure of the system has changed in these examples, the feedbacks generated from increasing demand and overextraction remain the same.

Table 3
List of Symbols and Abbreviations

	Description
A	community adaptation
a	efficiency constant of service recovery
b	growth rate of service deficit
C	capital
c_1	coupling parameter of service deficit onto service management
c_2	coupling parameter: direct shock impact on service management
CNHE	coupled natural-human-engineered system
CP	capital portfolio
CPA	capital portfolio approach
CT	mean crossing time
CV	coefficient of variation
F	financial capital
I	infrastructure
lpcd	liters per capita and day
M	service management
MC	Mexico City
n	coefficient
P	management power
r	maximum depletion rate of service management
R	robustness
RP	robustness portfolio
t	time
UB	Ulaanbaatar
W	water resources
α	mean shock magnitude
β	scaling constant signifies scale at which M degradation begins to level off
Δ	service deficit
λ	mean shock frequency
μ	mean value
ξ	shocks

Averages are commonly used to represent entire cities. However, intraurban heterogeneity can be significant with different urban water resilience regimes within the same city, as we demonstrated for Ulaanbaatar's split water system, where 60% of the population with low adaptive capacity lives under conditions of high insecurity. Adaptation (or coping) for meeting demands is often left to the urban poor, both on a daily basis and in response to disasters (Béné et al., 2014; Brown & Westaway, 2011; Waters & Adger, 2017), and the relative cost incurred to these communities is disproportionate (Chelleri et al., 2015). While the system dynamics model demonstrated here does not quantify the cost of adaptation (economic, health, social, etc.), accounts of the local conditions illustrate the high price that communities pay for the little adaptation they can afford (Potter et al., 2010; Wutich & Ragsdale, 2008). Such conditions are characteristic of rapidly developing cities in many African and Asian countries and concern millions of people across the globe (Bell & Hofmann, 2017; Gopakumar, 2009; Sullivan, 2002; WORLD BANK, 2015; Zug & Graefe, 2014).

At the other end of the gradient, water secure and resilient cities have fully developed their capitals ($CP \approx 1$), thus maintaining high levels of services and ability to instantly recover services even in the case of large and recurring shocks (here: Melbourne, Berlin, and Singapore). Similar characteristics of the CPA and thus model behavior are expected for cities in most of Europe, North America, Australia, and parts of Asia.

While the development of excess water infrastructure creates a buffer against natural variability and the effects of drought, it also creates large sunk-cost effects and high maintenance costs. It can make cities inflexible in responding to changing demands and environmental conditions. Situations of excess capital such as those found in Melbourne apply to other economically advanced regions with large hydroclimatic variability,

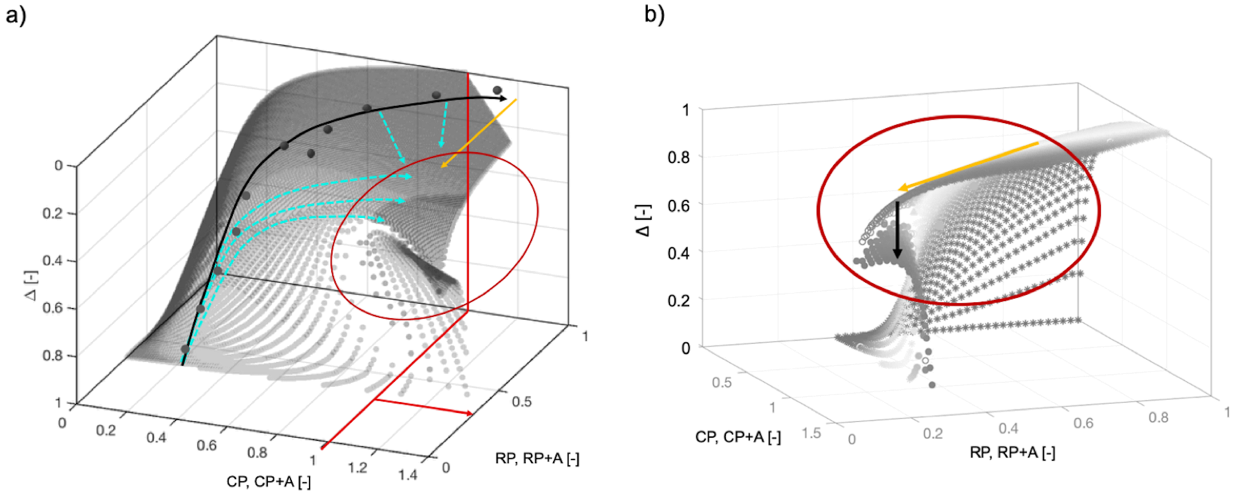

Figure 4. Schematic illustration of a tipping point in the rigidity trap with long-term trajectories of urban water systems under local and global change. Circled area indicates the rigidity trap. (a) Proposed trajectory of water supply systems under current governance paradigms (black solid line with dots schematically representing case studies) and potential future pathways under local and global change pressures (light blue dashed lines). Local increase in capital availability attained through development of excess capital (red arrow pushing systems across the CP = 1 threshold) and global change pressures (yellow arrow leading to a loss of RP) can push cities into the rigidity trap, illustrated by the fold in the resilience landscape (highlighted in Figure 4b). Dashed arrows (light blue) pointing down indicate trajectories of "decline," dashed trajectory lines from bottom left indicate pathways of from low security and resilience into transition, constrained by global change pressures in achieving high security and resilience. (b) Possibility of tipping points illustrated by the fold in the resilience landscape. Figure 4b is the same resilience landscape as in Figures 3 and 4a, rotated around the vertical axis to highlight the bifurcation area. CP = capital portfolio; RP = robustness portfolio

such as other cities in Australia and the U.S. Southwest. Increasing global pressures resulting from climate change, ecosystem degradation, and increasing urbanization will require a more transformative approach to urban water governance, as we discuss below.

4.2. Possibility of Tipping Points

Our model-data analysis also shows the possibility of regime shifts after crossing a tipping point indicated by the fold in the resilience landscape for high levels of CP and low levels of RP. While we did not find data for cities existing in the rigidity trap, which marks the area of bistable states or tipping points, recent urban water (near-) emergency situations indicate increasing pressures resulting from global and climate change. This may change the trajectories of urban water systems with consequences on the coevolution of urban water security and resilience and thus shift the predominance of cities residing in single stable state regimes toward multiple stable state regimes and into collapse. Emergency situations, which indicate such shifts are "Day Zero" scenarios in Cape Town in 2018 (Maxmen, 2018; Parks et al., 2019), and threats of water rationing in Rome (Giuffrida & Taylor, 2017). So far, returning rains or the installment of desalination plants in proximity to the coast (e.g., in the case of the millennium drought in Melbourne and other Australian cities) has allowed cities to recover to their original levels of services. However, changing rainfall patterns caused by climate change may permanently reduce the availability of water resources (IPCC, 2018), so that "excess infrastructure capital" (e.g., large storage reservoirs or river diversion projects) may no longer be a guarantee of urban water supply security. Therefore, gradual shifts in climate patterns, combined with the conventional response of enlarging the urban water footprint, could move systems into an area of the rigidity trap, where gradual loss of robustness and/or shocks can push cities across the tipping point into collapse. Figure 4 schematically illustrates the point. Yellow arrows represent global change pressures pushing systems from resilient into rigid regimes.

Other factors can contribute to the loss of robustness, such as a growing global population, increasing competition or water quality impairments. Contamination of rivers has made potential sources of drinking water unusable in Beijing (China; Qing, 2008; Tingting, 2017). Salinization of groundwater due to overpumping is a concern in coastal and/or (semi) arid areas around the world, such as in Amman (Hadadin et al., 2010), and the contamination of groundwater from agricultural and industrial pollution threatens the safety and sustainability of water supply, for example, in Berlin (Henzler et al., 2014). Where current strategies for increasing security lead to excess capacity and "hides" the possibility of sudden service loss due to slow onset events or even in the absence of shocks ("false sense of security"; Ishtiaque et al., 2017), such strategies may become decreasingly affordable under global change scenarios. Warning signals that have become widespread in cities around the world indicate the pressing need for a transformation of urban water supply systems, in order to maintain sustainability (i.e., long-term resilience; Chelleri et al., 2015; Folke et al., 2010; Meerow et al., 2016; Scheffer et al., 2009).

Global change pressures may also prevent cities from reaching security and resilience, as they evolve from low security and resilience through the transition phase. Current, supply-oriented strategies that focus on increasing supplies by enlarging urban water footprints (McDonald et al., 2014) may no longer satisfy urban water demands (Floerke et al., 2018) and push cities from transition into a rigid regime, instead of into a resilient regime (see Figure 4a). Whenever possible, past experience and awareness of risk lead urban managers to develop capital robustness, hence creating the basis for short-term resilient behavior. Governance strategies must embrace long-term resilience and build robustness that does not create trade-offs for sustainability (Chelleri, Waters, et al., 2015; Meerow et al., 2016). Maintaining sufficient flexibility to adapt, social learning and adaptive management allow a coevolution of security and resilience. However, internal factors (inflexibility/rigidity of developed systems) may also lead to lock-in, such as when cities build infrastructure to secure water resources, which they cannot afford to maintain over time or which lose their reliability due to changing rainfall regimes as explained above. On the other hand, external factors (global change pressures) may constrain the "adaptation space." Thus, current management strategies imply an impending failure for all types of cities presented here.

This calls for a modeling approach that integrates fast and slow variables that represent different, overlapping processes of degradation and recovery and, ultimately, transformation. The long-term evolution of urban trajectories will be influenced by cross-scale impacts, such as climate change and the degradation of ecosystems. Paradigm shifts toward demand management and closed water cycles will be needed in the future to achieve water security and resilience. First steps are being taken, such as developing a "water-sensitive city" in Melbourne (Ferguson et al., 2013) and efforts toward a closed urban water system in Singapore (Joo & Heng, 2017). As long as such strategies are developed with a sole focus on the water sector, trade-offs will remain (e.g., in the water-energy nexus) that have the potential of constraining the long-term resilience of such systems (Lenouvel et al., 2014; Liu et al., 2018; Romero-Lankao et al., 2018).

4.3. Future Research

Despite the aggregation of multiple capitals and robustness metrics, as well as several types of shocks into single variables, we were able to show dynamics of urban water systems, and outcomes are consistent with observations for the seven case study cities. Recovery times are fast when capital availability and robustness are high, while lack of CP and RP leads to slow recovery in nonresilient cities. Uncovering the accurate time scales will require comprehensive observational data of recovery times after a range of different types and magnitudes of shocks for multiple city types, which to date are rarely recorded (Cutter & Emrich, 2015).

Additional research and monitoring of relevant data are also necessary, in order to better understand the roles of each of the five capitals. Cascading and unexpected shock pathways could be accounted for in alternative shock terms, and application of a more refined disturbance concept would allow unpacking the interaction dynamics of CNHE systems in response to shocks (Grimm et al., 2017). Alternative models and additional data could be used to evaluate the interactions among the five capitals, as well as to assess interactions between informal settlements and areas served by public services (e.g., tapping into public water pipes, movement of residents between water service areas for use of shower, and laundry facilities in neighboring districts).

External drivers and social change resulting from global change processes will alter the balance between degradation and recovery, and the values of CP and RP, as well as shock regimes in the long term. Gradual changes of capital availability and robustness over time and in response to shocks will allow modeling the long-term evolution of urban water security and resilience, with the resulting trajectories tracking the changing locations of fixed points of cities over time. Here, we present cities with different levels of water security development as a "space-for-time" concept, instead of reconstructing the long-term evolution of individual cities (see Figure 4a). Future scenarios incorporating global change impacts may result in cities being pushed into the area of multiple stable states, where $CP > 1$and $RP < 0.3$ unless transformational strategies are approached.

5. Conclusions

Our results expand the systematic understanding of urban water resilience with quantitative insights into the behavior of real-world CNHE systems in response to shocks and disturbances. This includes the emergence of stable states, resilience and regime shifts, as well as the role of community adaptation in the resilience of urban water supply systems. First, we found that under current conditions, urban water systems tend to coevolve in terms of security and resilience. Second, we propose that global change has the potential to create trade-offs between measures aiming at increasing security by developing an excess in capital availability and the robustness needed for maintaining services under increasing global change pressures and thus driving systems across tipping points into alternate resilience regimes. Our model simulates cycles of loss and recovery to a single stable state and can be interpreted as short-term resilience (Meerow et al., 2016). While the simulated time series cover intermediate scales of years to decades, we suggest that the long-term trajectories of cities over multiple decades to centuries are implied in a space-for-time principle, where the selected case studies represent different levels of development and decline along the security and resilience gradient. This can be considered as the evolution of long-term resilience (Meerow et al., 2016), which opens the question of sustainability. The combined effect of increasing water scarcity and quality impairments of contested water resources will exacerbate water security issues with the possibility of tipping points indicated by the fold in the resilience landscape. Scenarios of future urban water security demonstrate that global change will alter patterns of resource availability, as well as increasing competition between sectors and cities (Floerke et al., 2018; Hoekstra & Mekonnen, 2012; Jenerette & Larsen, 2006). Therefore, future investigations should include sustainability considerations for transforming governance strategies for urban water security and resilience.

We found deep uncertainty in the resilience of urban water systems resulting from contingency on the disturbance regime, as indicated by the variability in survival periods for transition cities, and nonresilient and insecure cities. Whether or not a system can fully recover back to its stable state after a shock also depends not only on its capital portfolio but also on the timing and magnitude of recurring shocks. This indicates that past experiences of shocks and recovery are not a valid indicator of future dynamics. Such uncertainty resulting from nonstationary forcing and temporal shifts in model parameters is problematic for predictions used for management. Thus, guidance provided should be in probabilistic terms, as with most models, not as deterministic forecasts. Compilation of data from several case studies and incorporating long-term shifts in drivers of coupled system dynamics are important directions for future research. Such data-model synthesis efforts are essential for developing guidance to urban managers and policy makers for the future of urban water resilience.

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