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Integrated assessment of urban water supply security and resilience: towards a streamlined approach

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Abstract
Urbanization and competing water demand, as well as rising temperatures and changing weather patterns, are manifesting as gradual processes that increasingly challenge urban water supply security. Cities are also threatened by acute risks arising at the intersection of aging infrastructure, entrenched institutions, and the increasing occurrence of extreme weather events. To better understand these multi-layered, interacting challenges of providing urban water supply for all, while being prepared to deal with recurring shocks, we present an integrated analysis of water supply security in New York City and its resilience to acute shocks and chronic disturbances. We apply a revised version of a recently developed, quantitative framework ('Capital Portfolio Approach', CPA) that takes a social-ecological-technological systems perspective to assess urban water supply security as the performance of water services at the household scale. Using the parameters of the CPA as input, we use a coupled systems dynamics model to investigate the dynamics of services in response to shocks—under current conditions and in a scenario of increasing shock occurrence and a loss of system robustness. We find water supply security to be high and current response to shocks to be resilient thanks to past shock experiences. However, we identify a number of risks and vulnerability issues that, if unaddressed, might significantly impact the city's water services in the mid-term future. Our findings have relevance to cities around the world, and raise questions for research about how security and resilience can and should be maintained in the future.

1. Introduction

Current investigations of urban water supply security highlight the challenges arising from competing water demand for urban, agricultural, and industrial uses [1], as well as from rising temperatures and dynamic weather patterns resulting from climate change [2]. At the same time cities are also threatened by chronic and acute shocks occurring at the intersection of rapid urbanization, aging infrastructure, inflexible institutions, global economic interdependencies, and the increasing frequency and magnitude of extreme weather events, such as floods, droughts, heat waves, and severe storms or wildfires [3]. Thus, cities must simultaneously strengthen urban water supply security, while also ensuring the robustness and resilience of services in the face of risks and uncertainty [4].

Here, we define urban water supply security as the availability, access, affordability, reliability, continuity, and qualitative safety of water supply services delivered at the household level for all citizens [5]. Robustness is defined as the ability of the system to buffer and persevere in the face of shocks, and to recover and reorganize in response to disturbances [6–9]. While robustness is the combination of resistance (the ability to buffer shocks and persevere) and resilience (the dynamic response of recovery and reorganization in response to shocks), we use the terms robustness and resilience synonymously here (see section 2.2 for further explanation on the use of the two terms). Increased security is typically characterized by a decrease in the variability of service performance [10], which in turn is achieved by enhancing robustness and resilience: A diversity of sources, redundancies in the supply network, and the capacity to assure emergency response through tight feedback loops allow the system to buffer and respond to shocks [6, 11]. Structural measures that enhance robustness and resilience include multiple water-main lines conveying water from the source into the city from where it is distributed, a modular organization of water distribution within the city to limit damages due to pipe bursts or contamination events, and a diversity of sources, such as surface, ground, and recycled water. Thus, increased supply security is often achieved in conjunction with increased resilience [12].

The quantification of water security generally, and urban water supply security more specifically, is typically approached either through a quantification of water availability in local, regional or global studies ('resource-based' metrics), or the experience of water security at the individual, household, or neighborhood scale determined through case studies [4, 13]. Recently, quantitative frameworks that integrate biophysical resources (water, ecosystems, built infrastructure) and institutional capacities for (urban) water management have gained attention in the water security literature ([14–19] for reviews see: [13, 20, 21]). While resource-based approaches have also developed scenarios of future water security [1, 22], more integrative assessments of urban water security remain static snapshots in time [23, 24].

The resilience of urban systems, including physical infrastructures and the services they provide, is a function of human responses and their adaptive capacity required to recover infrastructure failures [25–29]. Despite this recognition, dynamic assessments and modeling studies of urban water resilience that explicitly capture the human response to shocks and disturbances for recovering these systems remain rare. Exceptions are the management of reservoirs in response to urban and agricultural demands [30], or in response to flood and drought cycles [31]. Rasoulkhani and Mostafani [32] simulated the reliability of water supply services resulting from the interaction of pipe network degradation and their recovery by social agents. The emergence of poverty traps resulting from a lack of water security-related investments was modeled by Dadson *et al* [33], and Muneeperakul and Anderies [34] presented a stylized model that showed the emergence of different resilience regimes driven by financial incentives (taxes) and resulting from the dynamic interactions of resource users and public providers with infrastructure and the natural environment.

Two recent studies building on each other presented a methodology that addresses these tensions. The first proposed a social-ecological-technological systems (SETS) approach (Capital Portfolio Approach, CPA) for quantifying urban water supply security with explicit attention to the adaptive capacity of urban managers and community adaptation at the household scale interacting with resource availability and infrastructure functioning [5]. The second presents a coupled systems dynamics model using input parameters from the CPA to quantify urban water resilience by generating dynamic time series simulations of urban water services, and their response to shocks and recovery [4]. Rather than being a predictive model of long-term coupled dynamics, this model focuses on the adaptive capacity of a system emanating from its institutions and infrastructure—much-needed research in the coupled water systems domain [35]. The two approaches have been applied to seven diverse cities worldwide in Krueger *et al* [4, 5], and to Qingdao (China) in Liu *et al* [36]. The systems dynamics model builds on Klammler *et al* [27], who represents the coupled dynamics of infrastructure services and adaptive management mobilized to recover services in response to stochastic shocks.

We use these interlinked approaches to assess urban water supply security and resilience in New York City (NYC) as a case study. To this end, we first revise the CPA framework to make it more streamlined and tangible. We then apply the CPA to NYC's water supply system and use the results as input data to run the model for the assessment of the system's resilience. Finally, we develop a realistic scenario for how NYC's water security and resilience may evolve in the mid-term future (until around 2050) under the pressures of climate and land use change and aging infrastructure, based on anticipated changes and potential risks highlighted in the literature.

2. Methods

2.1. Case study and data sources

New York City (NYC) is a large, densely populated city (NYC: 8.8 million inhabitants, >10 000 persons km^{-2})[1], located at the mouth of the Hudson River on the US North Atlantic east coast. The city receives its water from a network of 31 surface water lakes and reservoirs, reaching a distance of up to 188 km from the city center [14]. The majority

[1] NYC Census data for 2020: www1.nyc.gov/site/planning/planning-level/nyc-population/2020-census.page##2020-census-results (last accessed 6 March 2022).

(96%) of water is supplied from the Catskill-Delaware watershed, whose pristine condition allows the distribution of water without prior filtration[2]. NYC is a role-model for water governance, represented by the conditions under which its watershed area is managed and legally underpinned through the Watershed Memorandum of Agreement (MOA), signed in 1997 between the city and representatives of the watershed communities [37]. Per capita water consumption has dropped significantly from more than 800 l per capita and day (lpcd) in 1980 to around 450 lpcd in 2020[3]—a drop which can be attributed to several factors, including increased ecological awareness of urban water managers, the recognition of multiple user interests for the water resources and natural surroundings of the watershed area, as well as the introduction of water metering in the 1990's (as one of the country's last major cities) [37]. In 2020, customers were charged $1.41 and $2.24 per m^3 for water supply and sewage services, respectively[4].

Although of role-model character, the security of NYC water supply and the governance of its water system cannot be taken for granted. Diverse urban, rural, and industrial interests must undergo constant negotiation and adaptation with changing power relations, and goals and interests for land use [38]. In the past, competing interests with urban water supply concerned farming, hunting, and recreation. More recently drilling for natural gas ('hydro-fracking') in the Marcellus shale, of which 4,100 km^2 underlies the Catskill-Delaware watershed, has entered the radar of the energy industry [39]. If introduced in the area, the toxicity of chemicals applied in the drilling process could threaten the city's water supply [39].

While the region's climate is generally humid, periods of drought, although of moderate economic impact [40], are acutely monitored by the city's Department of Environmental Protection (NYC DEP), and reservoir levels have repeatedly dropped below 50% over the past decades[5]. Looking into the future, He *et al* [22] predict that NYC will experience seasonal water scarcity by 2050 under a 'Middle-of-the-Road' scenario (SSP2 and RCP 4.5). Streamflow conditions are expected to become more flashy with more variable climate conditions [41], which could increase the frequency and severity of water turbidity and resulting gastrointestinal health impairments [42], and thus would require significant investment in filtration technology.

Infrastructure degradation requires constant attention: One of the two aqueducts transferring water from the Catskill-Delaware watershed into the city was detected to leak at a rate of around 75 000 m^3 a day since 1992. The city announced to repair the aqueduct in 2010, achieving its first milestone in 2019, and expected for completion in 2023[6]. Furthermore, 90% of all water is stored in a single reservoir (Kensico/Hillview Reservoir; 10% is stored in the Croton Reservoir), from where water is transferred to the city through three aqueducts. However, large parts of the city receive water through a single transmission line [43]. Thus, the reliance on a few major nodes (i.e. reservoirs and aqueducts) and the lack of redundancies make the water system vulnerable to systemic failures.

NYC is subject to recurring extreme events, including urban flooding, heat waves, hurricanes, and snowstorms, which, in the past, have caused the loss of lives and large economic damage [44]. While the city's water supply system has largely been spared in the past, these shocks have triggered cascading failures across critical infrastructure systems, with the largest impacts recorded for transportation systems, buildings, energy systems, and drainage [44]. In response to a number of adverse events, including the 9/11 attacks and Hurricane Sandy in 2012, NYC has invested into a range of resilience efforts [45], which are still challenged during recurring extreme events, such as the recent Hurricane Ida flooding [46], and the current Covid-19 pandemic. The latter has deepened intra-urban inequalities, as expressed in the higher rates of Covid-19 prevalence and economic hardship for the urban poor [47]. Such crises have the potential of diverting attention away from other, long-term public health issues, including water-related ones. For example, a recent study found lead contamination in 8% of water samples taken in NYC public schools [48].

We use publicly available data and municipal reports published by the NYC DEP, as well as secondary data found in the scientific literature to perform our analysis of the NYC water supply system. We include risks and vulnerability issues of concern identified in these data sources to develop a scenario in which the vulnerabilities of the system are highlighted, indicating areas that potentially need attention to reliably maintain the city's water services in the future. All data sources are provided along with the detailed data in the *supplementary information* (SI),

[2] NYC Drinking water supply and quality resport 2020: www1.nyc.gov/site/dep/about/drinking-water-supply-quality-report.page (downloaded 29 March 2021).

[3] NYC Water consumption data (per capita) provided by NYC OpenData: https://data.cityofnewyork.us/Environment/Water-Consumption-in-the-City-of-New-York/ia2d-e54m (last accessed 6 March 2022).

[4] NYC Water Board water and sewer rates: www1.nyc.gov/site/nycwaterboard/rates/rates-regulations.page (last accessed 6 March 2022).

[5] NYC DEP Historical Drought and Water Consumption Data: www1.nyc.gov/site/dep/water/history-of-drought-water-consumption.page (last accessed 6 March 2022).

[6] NYC DEP Announces major milestone for Delaware Aqueduct repair as tunneling machine completes excavation (article dated 19 August 2019): www1.nyc.gov/site/dep/news/19-062/dep-major-milestone-delaware-aqueduct-repair-tunneling-machine-completes#/0 (last accessed 6 March 2022).

and we reference the sources where data are mentioned in the text.

2.2. Capital Portfolio Approach for assessing urban water supply security

We quantify security and robustness of urban water supply using an updated version of the Capital Portfolio Approach (CPA) developed in Krueger *et al* [5]. This integrated SETS approach [49–52] combines city- and household-scale perspectives. It quantifies the multi-dimensional nature of urban water supply in terms of the services that citizens receive at the household level, averaged over the entire urban area. These services are characterized by adequate access, quantity, quality, continuity, reliability, and affordability of water supply. Five 'capitals' (natural, physical, financial, institutional, and community capitals) contribute different functional elements to the security of urban water supply services, which we measure in terms of overall system performance: (1) 'Natural capital' (N) contributes the *functional element* of water *availability* at the city level; (2) 'Physical capital' (P) refers to the performance of infrastructure resulting from the availability and quality of storage reservoirs/tanks, treatment facilities, and distribution networks. P ensures the functional elements of *access, safety* (safe-to-drink quality), and *efficiency* (minimized water losses). (3) 'Financial capital' (F) is a supportive functional element, as it can be converted into other forms of capital, e.g. by investing into the construction of new infrastructure, and for the operation and maintenance of the existing system, including salaries paid to utility employees. (4) 'Institutional capital' (I) refers to the efficacy of management institutions, which contribute to the functional elements of *management efficiency, reliability* and *affordability* of water supply services. Aggregation of these first four capitals produces a metric representative of *public* water supply services. When public services are unable to meet demand, the fifth capital, community adaptation ('community capital', A) becomes necessary. A refers to individuals' and households' actions for dealing with service deficits, such as sharing water among households, buying water from stores or boiling water to make it safe to drink. A is a coping function that complements or replaces public water supply services provided through the four other capitals.

Table 1 provides an overview of the elements of the CPA. The first column indicates the CPA dimension (security/robustness), the second column indicates the functions that the capitals contribute to security/robustness, column three indicates the capital, and column four describes the individual metrics that are used to quantify each capital. The values we calculated for NYC are shown in the last column. Details of the calculation methods and reasoning behind each metric, as well as information about the adjustments made to the original method are described in the *SI*. Unless otherwise indicated in brackets, we determined binary values of 1, where the data sources indicated an existence of the metric characteristics, and 0 where we found no evidence, or indication of a lack of these characteristics.

Robustness and resilience are measures of the dynamic response of a system to a specific set of challenges. The robustness metrics add functionality in terms of the resistance to (or buffering of) shocks, the ability to respond to shocks by recovering impaired services, and to adapt to changing conditions. In contrast to the relationship between capitals and the functions they fulfill for security, in the robustness dimension functions are not assigned to a specific capital, as these features interact in the event of shocks to produce a (more or less) robust response. In the methods applied here, the term robustness was used in the CPA assessment [5]. The term resilience was used, taking the CPA values as input, to simulate the dynamic response of the system and investigate the potential of regime shifts [4] (see also section 2.3). In the following, we maintain the two terms with reference to these two approaches.

2.2.1. Aggregation of capital metrics

Where multiple metrics exist for a single capital, they are aggregated as follows: In most cases, we calculated the simple average (geometric mean) across metrics for each capital. This applies to capitals I, P_R, F_R, I_R, A_R, where subscript R indicates the robustness of the respective capital. The sum of metrics composing N_R are divided by 18 to produce a value between 0 and 1.

P is calculated as:

$$P = h * S_W - q * W_{\mathrm{Drink}} \tag{1}$$

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

$$S_W = \frac{\mathrm{UWA} - W_{\mathrm{leakage}}}{D_W} \tag{2}$$

By definition $S_W \leqslant$ (RHS) in equation (2). $W_{\mathrm{leakage}} = \mathrm{leakage}\ [\mathrm{m^3\ y^{-1}}]$, $D_W = \mathrm{demand}\ [\mathrm{m^3\ y^{-1}}]$. Thus, when D_W exceeds urban water availability (UWA), S_W can be <1. When water is not delivered at drinking water quality ($q = 1$, otherwise, $q = 0$), households must treat water at home, use alternative sources for drinking, or risk falling sick. Thus, the fraction of *drinking* water over total demand (W_{Drink} [-]) is subtracted from the public service term on the RHS of equation (1). Drinking water demand is 7.3 $\mathrm{m^3\ cap^{-1}\ y^{-1}}$, equals 20 lpcd (standard recommended by the World Health Organization):

$$W_{\mathrm{Drink}} = \frac{7.3 * pop}{D_W} \tag{3}$$

where pop [cap] is the total urban population. When $P = 1$, all available urban water resources are delivered

Table 1. Metrics of the Capital Portfolio Approach for quantifying the security and robustness of water supply, adapted from [5]. Unit values are dimensionless [-], and metrics are binary (1/0), unless otherwise stated. Values for NYC result from our analysis and represent current conditions, whereas values in parentheses represent the high risk, low robustness scenario (if different from current scenario). Reprinted from [5] Copyright (2019), with permission from Elsevier.

CPA dimension	Function	Capital	Metric		Value NYC
Security	Availability	N	Available water relative to security threshold (100 $m^3 cap^{-1} yr^{-1}$) [ratio]		1.69
	Access	P	Home connection to pipe network [fraction of households, including formal and informal settlements]		1
	Safety		Delivers safe-to-consume quality [fraction of households]		0.92 (0)
	Efficiency		Leakage [fraction of supplied water volume]		0.12 (0.20)
	(Supportive)	F	Sector income/sector spending multiplied by P to account for investment needs		0.94 (0.67)
		I	Institutional efficiency	Clear management structures and responsibilities with information sharing protocols	1
				Information feedback-loops	1
	Efficiency		Accountability	Mechanisms for follow-up of customer complaints	1
	Reliability			Corruption Perception Index > 50	1
				Administrative losses < 10%	1
	Affordability			Affordability of water services (<5% of household income)	1
			Regulatory complexity	Urban-urban/urban-rural resource allocation strategies	1
				Transboundary agreements (if not applicable = 1)	1
				Mechanisms for groundwater management	0
				Mechanisms for surface water management	1
	Coping	A	Water supply services covered by household [fraction]		0 (0.15)
Robustness	Resistance/ Buffering capacity	N_R	Source diversity and redundancy (4 levels; 1 = single source, 2 = one source type, 3 = two sources & types, 4 = multiple source types)		2
			Buffering capacity (storage-to-flow ratio, 4 levels; 1 = high stress: <0.2–4 = no stress: >0.6)		4 (3)
			Import independence—4 levels (1 = high stress: >0.5–4 = no stress: <0.15)		4 (3)
			Quality control (4 levels; 1 = monitoring only, 2 = emissions regulations, 3 = source control & polluter pays, 4 = precautionary principle)		4 (2)
			Wastewater treated [fraction]		1
			Households covered by sanitation [fraction]		1
	Response to shocks	P_R	Modularity source-to-sink		0
			Anticipatory maintenance		1 (0)
			Emergency solutions for power failures		1 (0)
			Continuous water supply		1
			Leakage monitoring		1 (0)
			Materials age <50 yrs (alternatively: infrastructure rating)		0
			Redundancy of critical nodes		0
			Possibility of emergency zone isolation		1 (0)
	Adaptability	F_R	Cost recovery		1 (0)
			Middle income city		1
			Energy autonomy		1 (0)
		I_R	Emergency operations planning		1 (0)
			Capacity to improvise		1
			Inter-sector coordination in operation and management		0
			Training & innovations for resilience and sustainability		1
			National support planning		1 (0)
			High city ranking		1
	Resilience	A_R	Median income > WB middle income threshold		1
			Households have access to alternative services		1 (0)
			Household storage capacity >7 d		0
			Households have access to information about system functioning		1 (0)
			Social capital (active community structures)		1
			Households treat water at home		0 (1)
			Households have direct access to resources		0

at drinking water quality to all households at demanded volumes (providing the functions of *access, safety*, and *infrastructure efficiency*).

A is an aggregate measure of (a) additional water resources accessed by the community (W_{extra}); (b) supply gaps bridged by storing and rationing water use at the household level (g), and (c) the water quality term from equation (1), which is added, if water is not delivered at drinking water quality (equation (4)):

$$A = \frac{W_{\text{extra}}}{D_{\text{W}}} + g * \left(1 - \left(S_{\text{W}} + \frac{W_{\text{extra}}}{D_{\text{W}}}\right)\right) + q * W_{\text{Drink}}. \tag{4}$$

The supply gap (g) is a fraction of time, e.g. water delivered on one day per week has a supply gap of 6/7. Data for the attributes of A are not routinely monitored and reported for cities in a standardized way. Thus, it can be difficult to quantify W_{extra}, unless household surveys or other prior work was done to quantify additional water resources accessed by households. Upper and lower uncertainty bounds can be calculated by setting $W_{\text{extra}} = 0$ (lower bound), and $W_{\text{extra}} = 1 - S_{\text{W}}$ (upper bound). When $A = 1$, available water services are fully covered by community adaptation, and public services = 0. Thus, when public water supply meets demand, citizens have no need to adapt, and $A = 0$. Therefore, A does *not* represent the community's *capacity* to adapt, but the *actual adaptation* to insufficient services. For all other capitals, values < 1 indicate a deficit, values > 1 indicate surplus.

Finally, to produce a single value for security and robustness, respectively, security values across the four capitals ($C_i \in [N,P,F,I]$) are aggregated using the harmonic mean, where the security of public water supply services is CP_{public}, and water supply security including community adaptation is $CP_{\text{total}} = CP_{\text{public}} + A$. Robustness values across the capitals are aggregated using the arithmetic mean ($RP_{i,\ \text{public}} \in [N_R, P_R, F_R, I_R]$), where the robustness of public water supply services is RP_{public}. Robustness including community adaptation is $RP_{\text{total}} = \Sigma RP_i/4$, with $RP_{i,\ \text{total}} \in [N_R, P_R, F_R, I_R, A_R]$.

The choice of harmonic mean for aggregating security metrics is based on the assumption that a significant lack of one of the capitals leads to a reduction of services overall, compared to a more balanced distribution of capital availability. Krueger *et al* [5] tested alternative aggregation methods, which showed that the arithmetic mean systematically overestimates measured services, while multiplicative aggregation tends to underestimate services for cities with service deficit. Addition of A emphasizes the substitutability, as people are forced to rely on self-services when public services are lacking. For robustness, a higher level of substitutability is realistic, which is why the arithmetic mean is chosen as the aggregation method here. For example, if infrastructure lacks robustness, P_R is reduced, but can be recovered by I_R. In addition, robustness of community adaptive capacity significantly increases system robustness, however, it is not independent of overall system robustness. For example, in case of a drought, all water resources will be impacted, including alternative water sources accessed by the community [5].

2.2.2. Risk estimation

Here, we define risk as the outcome of hazard, exposure, and vulnerability combined: A hazard becomes a risk when it has the potential to cause harm to a susceptible and vulnerable system [24, 53]. Vulnerability can be reduced through buffering capacity which increases robustness. Various types of chronic and acute shocks impact urban water systems, depending on a city's socio-political, economic, geographic, and climatic environment. Twelve types of hazards, which have the potential of producing shocks to the urban water supply system have been proposed by Krueger *et al* [5]. Hazards are qualitatively distinguished and categorized into two types: 'chronic' hazards are those that produce shocks with high frequency, but relatively low magnitude. Examples include land subsidence with the potential of causing gradual damage to infrastructure and contamination of piped water, competition for water resources, and illegal tapping into water pipes. Acute hazards are those producing shocks that typically occur with low frequency and high magnitude. Examples include earthquakes and landslides, industrial spills, terrorism and war, or severe floods. Table 2 presents an overview of the different hazards and the capitals that are susceptible to these hazards.

We reviewed the literature to identify which types of hazards pose a potential risk to NYC's water system. The results of this analysis are shown as binary values in the last column of table 2 (see SI for details). The average risk to each capital is calculated as the sum of potential occurrences per capital (column 5) divided by the sum of susceptibilities per capital (column 4). Together with the hazard frequency/magnitude type distinction, these are later translated into quantitative values, as described in section 2.3.2.

2.3. Resilience model

In the next step, we use aggregated values of security (CP), robustness (RP) and risk calculated in the CPA as input values into a coupled systems dynamics model to analyze the resilience of urban water supply services in response to shocks. The parameterization that translates CPA values into model parameters is explained in section 2.3.1. We apply the model developed by Klammler *et al* [27]. The model explores the interactions between water supply services provided through the infrastructure system and management response. More specifically, the model represents the deficit of services and the response of

Table 2. Identification of risks to urban water supply systems. Our estimate of potential occurrence is indicated as a binary value (1/0) under current conditions, values in parentheses are used to quantify risk in the high risk scenario (if different from current conditions). For a translation of the values listed in this table into quantified risk parameters used in the model, see section 2.3.2. Reprinted from [5] Copyright (2019), with permission from Elsevier.

Hazard category	Hazard type description	Hazard frequency/ magnitude type	Susceptible capitals	Potential occurrence in NYC
Geological and geographic hazards	Earthquakes, tsunamis, volcanic eruptions, landslides	Acute	*P A*	1
	Land subsidence and sea level rise	Chronic	*P*	1
Socio-economic stressors and geo-political threats	Socio-economic/ political changes/ unforeseen population growth (e.g. high immigration rates)	Chronic	*N P F I A*	0 (1)
	War/terrorism	Acute	*N P F I A*	1
	Illegal tapping into water pipes	Chronic	*P*	0
	Economic crises	Chronic	*F I A*	1
	Competition for resources	Acute	*N I*	0 (1)
Contamination hazard	Industrial spills (from upstream industry)	Acute	*N P A*	0 (1)
	Epidemic incidents through degraded infrastructure (e.g. in combination with floods)/potential of groundwater degradation from intensive farming, salt water intrusion, and lack of sanitary infrastructure	Chronic	*N P A*	0 (1)
Climate and weather-related hazards	Storms and wildfires	Acute	*P*	0 (1)
	Floods/drought	Acute	*N*	1
	Extreme temperatures (freezing & bursting of pipes)	Chronic	*P*	0 (1)

management to maintain services or recover service deficit. The deficit of water supply services is defined as a dimensionless state variable Δ [-]:

$$\Delta(t) = 1 - \frac{S(t)}{D(t)} \tag{5}$$

where t is time. $S(t)$ is the level of services available, and $D(t)$ is total service demand. In the following, we omit the explicit time dependence for brevity. We term $\Delta(t)$ the *scaled service deficit*, with $\Delta = 0$ representing no deficit ($S = D$), and larger values of Δ representing larger deficits, with a maximum of 1 when $S = 0$. The interactions of service deficit (Δ) and service management (M) represented as a coupled system are defined as follows (equations (6) and (7)):

$$\frac{\mathrm{d}\Delta}{\mathrm{d}t} = (1-\Delta)\,b - aM\Delta + \xi \tag{6}$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = (1-c_1\Delta)\,M(1-M) - r\frac{M^n}{\beta^n + M^n} - c_2\xi \tag{7}$$

Δ increases through the sum of demand growth and service degradation (rate b), and is recovered by service management with efficiency a (equation (6)). The replenishment of M is constrained by coupling with Δ through c_1 (equation (7)). For $c_1 \to 0$, the two systems are increasingly decoupled. The degradation of M is determined by the maximum depletion rate, r, and the depletion curve is described by parameters β (scale; half saturation point of maximum depletion rate) and n (shape). The choice of the exponent n is key to the possible existence of multiple equilibria and possibly more complicated limit-point sets.

Despite a high level of abstraction, the model includes representations of mechanisms affecting the system dynamics. The functional form of the model representing M (equation (7)) adopts two models used widely to describe the dynamics of ecological systems [27]: the logistic growth function for the replenishment of M (first term on RHS of equation (7); see [54]), and the Langmuir (or Hill-type) function for the loss of M (second term on RHS of equation (7); see [55]). The combination of these nonlinear equations can exhibit multiple stable states with regime shifts at defined thresholds [27]. They are suitable for describing the dynamics resulting from the balance of losses and gains of service management.

Stochastic shocks (ξ), which can be caused by natural hazards, socio-economic threats, or infrastructural failure (see table 2), lead to the loss of services, and drive the dynamics of the model. A Poisson sequence of Dirac impulses $\delta()$ $[1/T]$ of discrete buffered shocks ($\xi_i - \pi_c$) at times t_i acts as the external stochastic forcing of the system:

$$\xi = \sum_{i=1}^{\infty}(\xi_i - \pi_c)\delta(t-t_i)\,[1/T]\,. \tag{8}$$

Shocks modeled as the outcome of a Poisson process have mean frequency (λ), and exponentially distributed magnitude (α). The assumption of a random distribution of shocks seems adequate, as the shock time series result from the combination of a range of different types of hazards impacting services through the capitals (see [56]). Shocks are produced from the sum of two time series, one for chronic (high frequency, low magnitude events), and one for acute shocks (low frequency, high magnitude events). The severity of shock impacts depends on the system's buffering capacity (π), such that $\xi = \xi_i - \pi$. Censoring of shock severity is applied to the frequency of shocks, as suggested by Rodriguez-Iturbe *et al* [57]. Shocks impact Δ directly, and lead to a degradation of M through coupling parameters c_1 and c_2.

The dimensionless system is normalized to unit replenishment timescale in M ($t = t_{\text{real}}\, r_{\text{RF}}$, where r_{RF} is the rate of growth in M). This means that t can represent varying lengths of real time, depending on the magnitude of shock impacts and a city's ability to respond to shocks, which can be in the order of days or weeks (or less for resilient cities), or months to years (or even decades for non-resilient cities). For NYC, we assume t to be in the order of days, as the city's water system in its current condition is generally able to recover quickly from disturbances (see [4] for time estimations in other cities). Parameters are chosen such that the relation between the two time scales is $a \gg b$, causing the recovery rate in Δ to be significantly larger than the replenishment rate in M (by one or more orders of magnitude). This reflects the significantly slower dynamics in M with respect to Δ. We generate numerical simulations of time series of the two state variables $\Delta(t)$ and $M(t)$ using equations (6) and (7) and an ordinary differential equation solver (MATLAB ode45), applied separately to each time interval between shocks. Simulations are conducted for 1000 time units (or until complete failure occurs), 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. Following the approach in Klammler *et al* [27], we use scaled parameters and normalized equations, so that the model is non-dimensional. For the description of the derivation of the equations and the normalization of the parameters we refer the reader to [27].

2.3.1. Model parameterization

We assume the coupled system to be representative of the multi-dimensional nature of 'services' defined above (including availability, access, affordability, reliability, continuity, and qualitative safety), and thus, Δ and M to result from the interaction of the capitals. Therefore, we use aggregate water service security (CP, indicating the availability of capitals) and robustness metrics (RP) as input for quantifying the parameters of equations (6) and (7), and aggregated acute and chronic risks for quantifying λ in ξ. The following sections describing the model parameterization are taken from Krueger *et al* [4].

Growth in service deficit results from the sum of demand growth and service degradation. Capital availability (CP) is required for keeping up with demand growth, and capital robustness (RP) is required for service maintenance/recovery. Therefore, parameter b, which represents the sum of demand growth and service degradation, is calculated from the summed lack of capital availability and robustness, such that $b = (1-CP)+(1-RP)$. The efficiency coefficient a, responsible for the recovery of services through M increases with higher capital availability and robustness: $a = \Sigma C_i\ \Sigma R_i$, where $C_i \in [N, P, F, I, A]$ and $R_i \in [N_R, P_R, F_R, I_R, A_R]$. The impact of Δ on M is determined by coupling parameter c_1. The higher the robustness of the system, the greater the capacity to buffer this impact, therefore: $c_1 = 1-RP$. r corresponds to the maximum depletion rate, which is highest when capital availability and robustness are low. Thus, we assume that the depletion rate r corresponds to average lack of robustness and capital availability: $r = 1-(CP+RP)/2$. Coupling parameter c_2 indicates the direct impact of shocks on M. We assume that the ability to absorb shocks diminishes with decreasing capital availability and robustness.: $c_2 = r = 1-(CP+RP)/2$. The scaling constant β signifies the scale at which degradation of M begins to level off, which we assume to be the case when the level of robustness is reached: $\beta = RP$. 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 M degradation. n indicates how fast shocks impact M. It is set to: $n = \Sigma R_i$.

This parameterization assumes a strong correlation between key model parameters, which are determined by CP and RP. We assume that in urban systems, by definition $CP \neq 0$. Table 3 provides an overview of the model parameters and acronyms used.

Krueger *et al* [4] parameterized the model using seven real-world urban water supply systems as case studies, for which they quantified the CPA. They explored the occurrence of stable states though model simulation for the possible ranges of CP ($0 \leqslant CP \leqslant 1.4$) and RP ($0 \leqslant RP \leqslant 1$) as input, and tested the resulting parameter space for all parameters $\geqslant 0$ (which are calculated as: $0 \leqslant b \leqslant 2, 0 \leqslant a \leqslant 25$, $0 \leqslant c_1 \leqslant 1$, $0 \leqslant c_2 \leqslant 1$, $0 \leqslant \beta \leqslant 1$, $0 \leqslant n \leqslant 5$). They found that two non-trivial equilibria exist when $RP \lesssim 0.3$ and $CP > 1$ simultaneously, one with a high level of services that meets demand, and one with a low level of services, not meeting demand [4]. In this condition, a trivial equilibrium (unstable) also exists for no services.

Table 3. Overview of model parameters and input variables.

Parameter or variable	Description [all parameters are dimensionless]	Quantification
C	Capital availability (quantified as 'security' dimension), $C_i \in [N, P, F, I, A]$	See table 1 for each capital
R	Capital robustness, $R_i \in [N_R, P_R, F_R, I_R, A_R]$	See table 1 for each capital
CP_{public}	Security of public urban water supply services, $C_i \in [N, P, F, I]$	$CP_{\text{public}} = \frac{4}{\sum \frac{1}{C_i}}$
CP_{total}	Security of water supply services, including community adaptation, $C_i \in [N, P, F, I, A]$	$CP_{\text{public}} + A$
RP_{public}	Robustness of public water supply services, $R_i \in [N_R, P_R, F_R, I_R]$	$RP_{\text{public}} = \Sigma R_i/4$
RP_{total}	Robustness of water supply services, including community adaptation, $R_i \in [N_R, P_R, F_R, I_R, A_R]$	$RP_{\text{total}} = \Sigma R_i/4$
b	Sum of demand growth and service degradation	$b = (1-CP)+(1-RP)$
a	Efficiency coefficient	$a = \Sigma C_i \, \Sigma R_i$
r	Maximum depletion rate	$r = 1-(CP + RP)/2$
β	Half saturation point of maximum depletion rate	$\beta = RP$
n	Exponent (shape parameter)	$n = \Sigma R_i$
c_1	Coupling parameter; $\Delta \to M$	$c_1 = 1-RP$
c_2	Coupling parameter; direct shock impact on M	$c_2 = 1-(CP + RP)/2$
α_{chronic}	Magnitude of chronic shocks	0.03
α_{acute}	Magnitude of acute shocks	0.2
λ_{chronic}	Frequency of chronic shocks	$\lambda_{\text{chronic}} = \frac{\text{chronic shock score}}{\sum \text{chronic shocks}} \left(1 + RP_{\text{public}}\right)^{-1}$
λ_{acute}	Frequency of acute shocks	$\lambda_{\text{acute}} = \frac{\text{acute shock score}}{\sum \text{acute shocks} * 10} \left(1 + RP_{\text{public}}\right)^{-1}$

Klammler *et al* [27] explore the dynamics of the model through a combination of formal stability analysis, simulations and time series analyses to detect the potential for regime shifts in response to shocks where multiple stable basins of attraction exist. Here, we tested the parameters calculated for NYC through simulation (without shocks), initially setting $n = 1$ to compare the behavior of the model with results of Klammler *et al*, and then for the more interesting dynamics where $n = 2$. For these parameters, representing current conditions, the simulations suggest that there is at most a single non-trivial stable equilibrium when $n = 1$ (and none for public service under low robustness, but two for total services and low robustness). For $n = 2$, again for these parameters, there is a unique non-trivial stable equilibrium; but formal stability analysis predicts the possibility of multiple feasible stable equilibria for $n > 1$ for appropriate parameter regimes. We also explored a broader range of values of n without altering the other parameters for the NYC case. The simulation results, including simulations using the entire parameter range also tested in previous studies, can be found in the SI.

2.3.2. Shock regime

The disturbance regime results from the combination of chronic and acute shock time series, where ξ is always $\geqslant 0$. 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:

$$\lambda_{\text{chronic}} = \frac{\sum \text{chronic risks}}{\sum \text{chronic hazards}} \left(1 + RP_{\text{public}}\right)^{-1} \quad (9)$$

where the sum of chronic risks in the enumerator are the product of columns 3 (chronic hazard type) and 5 (susceptibility) in table 2, and the denominator is the sum of chronic hazard types found in column 3, table 2. According to Rodriguez-Iturbe *et al* [57], censoring (buffering) results in a lower frequency of shocks [27]. We apply this logic by censoring shocks proportional to $\text{RP}_{\text{public}}$.

Acute shock frequencies are assumed to occur an order of magnitude less frequently:

$$\lambda_{\text{acute}} = \frac{\sum \text{acute risks}}{\sum \text{acute hazards} * 10} \left(1 + RP_{\text{public}}\right)^{-1}. \quad (10)$$

Combined risks resulting from various causes can cause supply intermittence or other disruptions in water services. Krueger *et al* [4] reviewed typical chronic and acute shock magnitudes with and without buffering capacity. For chronic shocks, they assessed pipe network failures due to pipe bursts, and the ability to buffer such disruptions through the installation of isolation valves in a range of cities. For acute shocks, they found examples of water supply interruptions due to earthquakes and droughts, based on which they estimated $\alpha_{\text{chronic}} = 0.03$ as the mean magnitude for chronic shocks and $\alpha_{\text{acute}} = 0.2$ for acute shocks. We maintain the same values for producing a stochastic shock regime as the sum of chronic and acute shock time series. Shocks are added (subtracted) to service deficit and service management in each time step.

2.3.3. Limitations of the model

The availability of high-resolution time series in response to shocks for all five capitals would allow the development of a more mechanistic model explicitly representing the dynamic interaction between the capitals. In absence of such data, the aggregated response that we model here is associated with large uncertainty. Thus, our model explores the system's response to shocks, but we refrain from making estimates of more precise process interactions or of a quantification of data and model uncertainty. Results should therefore be understood as an exploration of possibilities, rather than a reproduction of reality or prediction of the future. Understanding resilience as the outcome of several interacting parts, whose individual dynamics and the interactions between them are not precisely understood, has analogues to the resilience of living organisms, such as the human body [58]. While it is not necessarily known exactly how the individual system elements (organs or capitals) interact, we can observe the aggregate response to shocks at the system level that results from capital interactions.

3. Results

3.1. Security and robustness of NYC water supply services

The results of the CPA analysis show that urban water supply security in NYC is high, at $CP_{\text{public}} = 1.02$, and $A = 0$. We found urban water supply robustness to be intermediate, at $RP_{\text{public}} = 0.83$, and very high for $\text{RP}_{\text{total}} = 0.98$. Below we present the results of the CPA analysis for each capital, discussing those metric values that contribute to either deficit or excess capital values. Figure 1 shows the aggregated results, and detailed values are presented in the last columns of tables 1 and 2. Table 4 shows the aggregated results as a color-coded dashboard. Security and robustness values of 1 indicate that services fully meet demand, and that a robust response to shocks can be expected, whereas $CP < 1$ and $\text{RP} < 1$ indicate deficits in security and robustness, respectively.

Natural capital: NYC's water resources receive high to excessively high scores on all metrics assessed for water resource availability and robustness. Average water availability in NYC is 169 $\text{m}^3\,\text{cap}^{-1}\,\text{y}^{-1}$, which is 1.69 times the security threshold of 100 $\text{m}^3\,\text{cap}^{-1}\,\text{y}^{-1}$ [5]. Robustness, however, scores 0.89, with deficits noted for source diversity and redundancy, given that the city relies on a single source type (surface water reservoirs). Potential risks affecting water resources include floods, droughts, and terrorist attacks, resulting in an intermediate risk score of 0.33 for N.

Physical capital: Infrastructure scores 0.88 on the security metric due to a leakage rate of 12% [59]. Robustness scores an intermediate-low 0.63, as large parts of NYC's water infrastructure needs renewal (average materials age >50 years low infrastructure rating),[7] infrastructure is designed in a highly centralized way (modularity value is 0), and there is a lack of redundancy of critical nodes. Given the existence of a number of risks, these shortcomings make the system prone to failure. As noted in the case study description, 90% of NYC water is stored in a single reservoir, and large parts of the city are served through a single transmission line [59]. Failure in one of these central nodes would significantly disrupt services for large parts of NYC's population. Potential risks (intermediate score: 0.33) affecting infrastructure include earthquakes, terrorism, and land subsidence, which causes potential damage to subsurface water infrastructure, especially in areas built on land reclaimed from the sea through landfills.

Financial capital: Income and spending were balanced (7% surplus) in the years considered here (2012–2017), however outstanding investment needs result in a financial security score of 0.94 (very high security). Financial robustness receives full score. Financial capital risks are high (score: 0.67) due to potential terrorism attacks that could damage the city's infrastructure and would place a burden on finances due to required investments for repairs and reconstruction, as well as the impact that economic crises can have on the municipal budget of NYC.

Institutional capital: Management efficacy scores high (security score: 0.90). A deficit of 0.1 results from a missing groundwater management strategy. Robustness of management receives an intermediate score (0.83), as there is little coordination across sectors in operation and management [60, 61]. Terrorism and economic crises could present a high risk to institutional capital (risk score: 0.5).

Community capital: Under current conditions, public water services meet demand, and therefore, community adaptation remains inactive (score = 0). Community robustness shows a deficit (0.57), because citizens are not prepared for supply failures: We assume that households do not maintain significant water storage capacity, nor have direct access to water sources (lakes, rivers, or groundwater wells), which they could tap into should the water supply system fail. Risks potentially affecting community adaptation include earthquakes, terrorism attacks, and economic crises (intermediate risk score: 0.43).

3.1.1. High risk, low robustness scenario

Future urban hazards are expected to increase due to climate change, increasing competition for land and resources, and infrastructure degradation. While we make no assumption about the probability of such a scenario, we aim to understand the challenges that urban managers could be facing in a plausible future scenario, and how their ability to respond to these

[7] https://infrastructurereportcard.org/state-item/new-york/(last accessed March 09 2022)

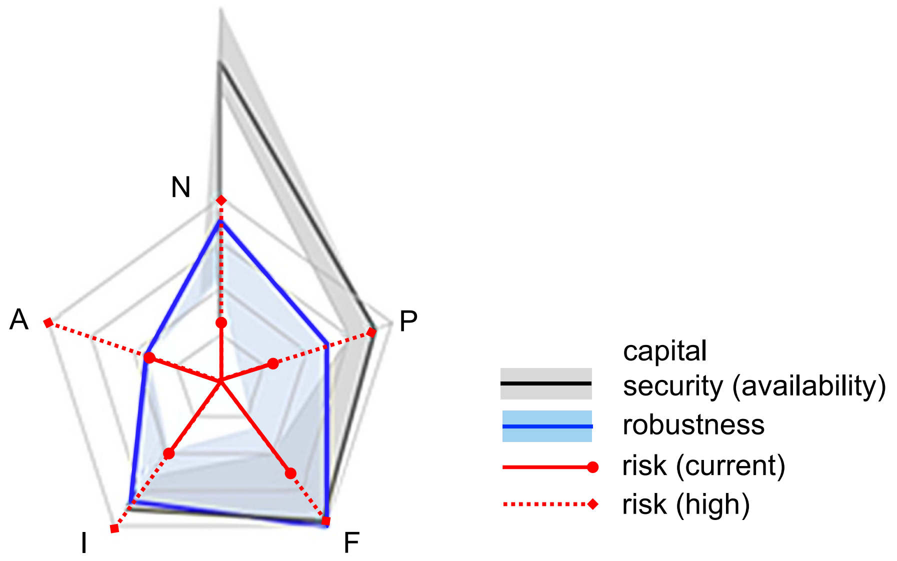

Figure 1. Aggregate results of the CPA analysis of NYC's water supply system. Axes are scaled between 0 (center of the radar plot) and 1 (outer edges). Capital security and robustness values < 1 indicate a deficit, values > 1 indicate surplus. For $A = 0$ community adaptation is inactive. Shaded areas for security (availability) represent variability (*N, F*) and the lower bound scenario (*P, F, I, A*). Risks increase from 0 (low) to 1 (high). Solid and dashed lines for risk represent current estimates and the high risk scenario, respectively.

Table 4. Color-coded dashboard showing results of the CPA analysis.

Capital	Security/ availability (C_i)	Robustness (R_i)	Risk	Low robustness scenario Availability	Robustness	Risk		Security, robustness color code	Risk color code
N	1.69	0.89	0.33	1.53	0.56	1.00	Legend	Excess (>1.0)	No risk (0)
P	0.88	0.63	0.33	0.75	0.13	0.89		Very high (0.95–1.0)	Very low (<0.1)
F	0.94	1.00	0.67	0.50	0.33	1.00		High (0.85–0.94)	Low (0.1–0.29)
I	0.90	0.83	0.50	0.90	0.50	1.00		Intermediate (0.70–0.84)	Intermediate (0.3–0.49)
A	0.00	0.57	0.43	0.05	0.43	1.00		Intermediate-low (0.5–0.69)	High (0.5–0.69)
Public	1.02	0.84	0.45	0.79	0.38	0.98		Low (0.35–0.49)	Very high (0.7–0.9)
Total	1.02	0.98	0.45	0.84	0.49	0.98		Very low (<0.35)	Extreme risk (>0.9)

pressures might impact the city's water services in the mid-term future. We assume 'mid-term future' to represent the next decades until around 2050. We include risks and vulnerability issues highlighted in the literature and publicly available data sources, and combine this with one potential option of management response.

High risk: In this scenario, we assume the city's water system to be challenged by the following risks in addition to those identified for current conditions (see table 2, values in parentheses):

1. Socioeconomic/ political changes/ unforeseen population growth: This could be an economic crisis resulting from, e.g. slow recovery from the current Covid-19 pandemic, rising energy prices in the context of climate change and the 'net-zero' CO_2 emission targets for the energy sector, political upheavals and a changing geopolitical landscape.
2. Competition for resources: Conflicting interests in the NYC watershed are negotiated within the framework of the MOA. The low robustness scenario accounts for a weakened MOA in terms of the conditions benefitting NYC's water security, and increasing pressures on water resources for agriculture (irrigation and pesticide/fertilizer use) and industry (e.g. hydro-fracking) [38, 39].
3. A weakened MOA and the location of industry in the city's watershed area could increase the risk of industrial spills with the potential contamination of water resources.
4. The combination of sea level rise and land subsidence in the NYC area could lead to water-related epidemic incidents through an increase in cracked and leaking pipes, sewer overflows and reverse flows due to the loss of hydraulic head [62, 63]. Epidemic episodes of gastrointestinal disease could also occur due to more flashy runoff events and increased water turbidity [42, 64, 65], due to which the Filtration Avoidance Determination granted to NYC by the USEPA would have to be revised [38, 66].

5. Storms and wildfires with the potential of damaging infrastructure: Hurricanes Sandy and Ida have demonstrated that NYC will likely need to prepare for a higher frequency of similar extreme events. While the city's water supply so far has largely been spared, power outages and other infrastructure failures can have cascading impacts on water supply services [3, 67, 68]. Such failure propagation is typical of complex, interdependent systems, caused by non-linear feedback mechanisms between the different urban subsystems and the capitals of the urban water supply system. Such cascading events could be particularly relevant in the case of a co-occurrence of multiple risks, such as storms or earthquakes.
6. Extreme temperatures: These could damage infrastructure within the city, in the watershed area, or the pipeline system connecting the two, and could lead to service failures.

We assume that continuous pressure resulting from these increased risks would manifest in a degradation mainly of water supply service robustness, with a few recognizable impacts also for capital availability/ security (see last column in table 1, values in parentheses). We discuss these changes below.

Natural capital (impacts from additional risks 1–4): We assume a moderate reduction in water availability due to increased competition for resources by 10%, from currently 169 $m^3\,cap^{-1}\,y^{-1}$ to 153 $m^3\,cap^{-1}\,y^{-1}$. Assuming constant population, this would diminish the city's backup capacity and require demand management during drought conditions. This scenario could potentially be exacerbated by climate change [22] or significant increases in population. We assume a reduction of the storage-to-flow ratio from level 4 (>0.6) to level 3 (0.3–0.6). Under current conditions, the MOA guarantees the city's access to the watershed's water resources, and the city owns portions of the watershed land area. In the low robustness scenario, we assume that the city looses its access and ownership rights, leading to an increased 'import dependence' from level 4 (<15%) to level 3 (15%–25%). Water resources under the MOA are protected under precautionary principle rules, which avoids potential source water pollution [38]. In the scenario we assume a reduction of water quality protection from level 4 (precautionary principle) to level 2 (emissions regulations), which could have an effect on nitrate and pesticide pollution from intensive farming, inadequate sanitary infrastructure in the watershed, and industrial pollution of water sources.

Physical capital (additional risks 1, 3–6): We assume leakage rates increase to 20% due to a reduced capacity for leakage monitoring and anticipatory maintenance, as well as a failure by the city to deliver drinking quality water. We further assume a lack of emergency energy supplies in the case of power failures (needed for drinking water and sewage pumping), as well as an inability to isolate different distribution zones in the case of an emergency.

Financial capital (additional risk 1): We assume socioeconomic and political changes to reduce the energy autonomy of the state of New York, requiring additional spending, as well as water system operations, maintenance and investment costs to no longer be recovered through water fees, leading to a degradation of financial security and robustness.

Institutional capital (additional risks 1, 2): We assume a loss in emergency operations planning, both at the urban and at the national scale.

Community capital (additional risks 1, 3, 4): We assume that households experience supply intermittence on average for one day a week, and the need to treat water before drinking, as the city is no longer able to reliably provide drinking quality water. Access to or availability of information on water system function becomes limited, such that feedback between customers and the water provider is constrained.

As a result, this scenario is characterized by extremely high risk (0.98), intermediate security ($CP = 0.73$), and low robustness ($RP = 0.38$). By activating community adaptation, security and robustness are increased to $CP_{\mathrm{total}} = 0.88$ and $RP_{\mathrm{total}} = 0.49$.

3.2. Resilience modeling of NYC water supply services

The model was solved for the following variables: (a) Fixed points of M and Δ (M_{fix} and Δ_{fix}). In the case of stable equilibria, these are attractors toward which the system converges in the absence of shocks. (b) Mean values (μ) and the coefficient of variation (CV) of M and Δ over the entire time series. (c) 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. The mean crossing time below the expected service deficit (1−CT) is used as the aggregate measure of resilience.

We ran several model simulations with results shown in figure 2: The first two panels (a), (b) represent the stochastic shock time series (equation (8)) for the current conditions of the NYC water supply system, and for the high risk scenario, respectively. The top rows in figures 2(a) and (b) represent chronic shocks (ξ_{chronic}), the middle row represents acute shocks (ξ_{acute}), and the bottom row represents the combined shock time series (ξ_{sum}), which were produced with input from the aggregated and combined chronic and acute risk estimates in the CPA. The latter are applied in the model to drive the dynamics of Δ and M. The dynamics of Δ and M

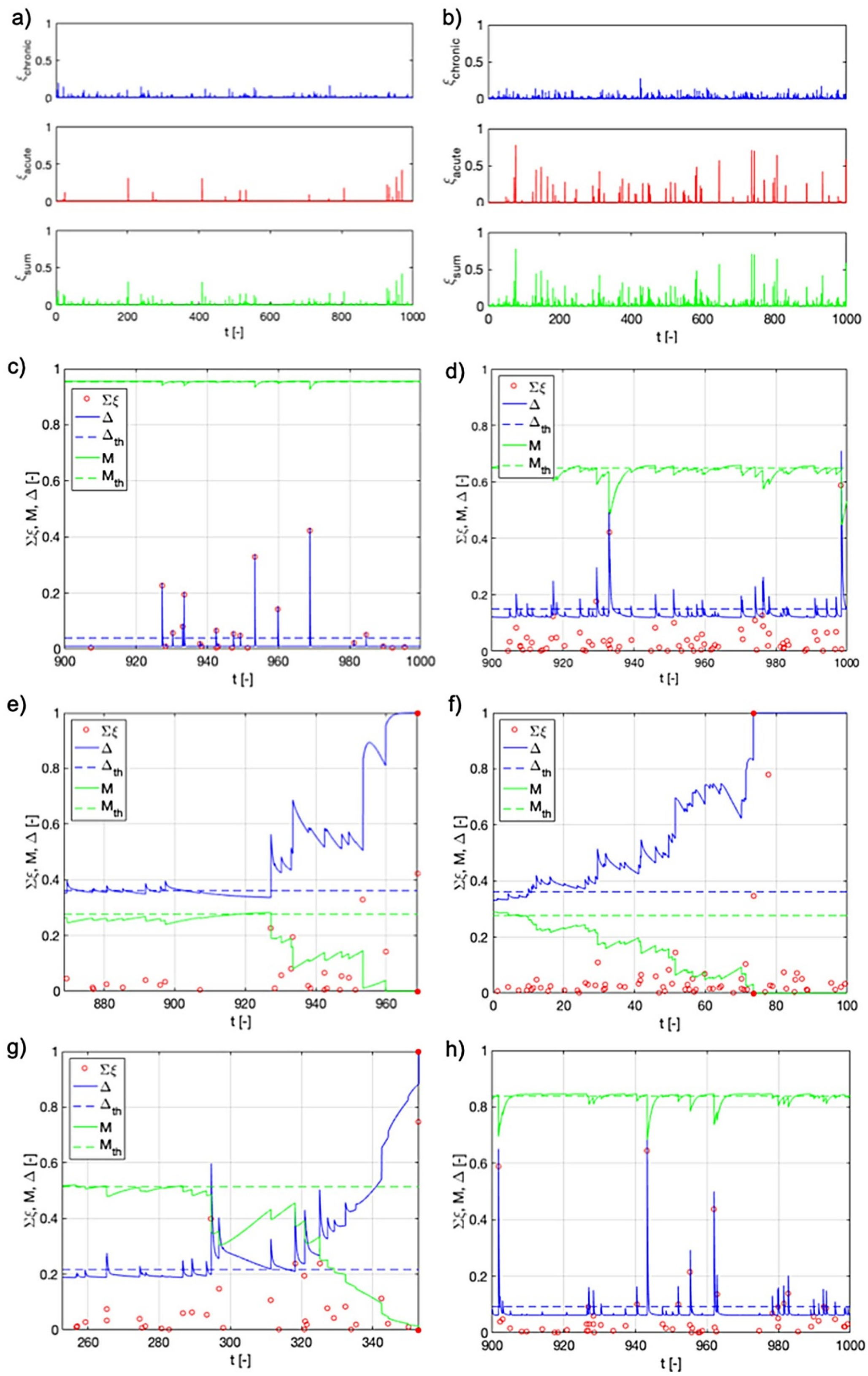

Figure 2. Resilience modeling results. Panels (a), (b) Shock time series of chronic (top row), acute (middle row), and combined shocks (bottom row). Panels (c)–(h): Dynamics of service deficit (Δ) and service management (M) in response to shocks (red circles, $\Sigma\xi$) showing last 100 time steps of $T = 1000$ or before system failure. Left panels: current risk; right panels: high risk scenario. (c) Current system conditions; (d) Low robustness scenario with community adaptation and (e), (f) without community adaptation. (g), (h) illustrative cases: (g) low robustness with high security; (h) high robustness, low security. (g) represents a case with multiple non-trivial equilibria. See SI (figure 2.5) for details.

Table 5. Input parameters and simulation results of the resilience model (compare to figures 2(c)–(f)).

Simulation	Model parameters			Numerical solutions				
		Public	Total		Low risk		High risk	
Current conditions (compare figure 2(c))	r	0.07	0.00	M_{fix}	0.96			
	n	3.35	3.92	Δ_{fix}	0.01			
	β	0.84	0.98	μ_M	0.95			
	c_1	0.16	0.02	μ_Δ	0.01			
	c_2	0.07	0.00	CV_M	0			
	a	14.74	17.29	CV_Δ	0.63			
	b	0.14	0.00	CTM_{below}	0.08			
	$\lambda_{chronic}$	0.18	0.18	$CT\Delta_{above}$	0.01			
	λ_{acute}	0.03	0.03					
					Public (figure 2(e))	Total[a]	Public (figure 2(f))	Total (figure 2(d))
Low robustness scenario	r	0.41	0.33	M_{fix}	0.29	0.6	0.29	0.66
	n	1.51	1.94	Δ_{fix}	0.33	0.12	0.33	0.12
	β	0.38	0.49	μ_M	0.23	0.65	0.17	0.63
	c_1	0.62	0.51	μ_Δ	0.40	0.12	0.50	0.13
	c_2	0.41	0.33	CV_M	0.21	0.02	0.47	0.57
	a	6.64	7.26	CV_Δ	0.22	0.10	0.29	0.26
	b	0.82	0.65	CTM_{below}	0.93	0.20	0.90	0.68
	$\lambda_{chronic}$	0.6	0.6	$CT\Delta_{above}$	0.64	0.02	0.86	0.09
	λ_{acute}	0.07	0.07	$t_{collapse}$	968.78	—	73.54	—

[a] Not shown in figure 2.

are shown in figures 2(c)–(h), with stochastic shocks ($\Sigma\xi$, red circles), service deficit (Δ, blue lines) which responds directly to the shocks, and service management (M, green lines) with a less pronounced response to shocks, especially where $c_2 \ll 1$.

Figure 2(c) represents the public water supply system in its current condition. It shows no fixed service deficit ($\Delta_{fix} = 0$, $S = D$), and an immediate return to full services in response to shocks. This indicates that services are provided as demanded, and citizens are unlikely to notice an impact of shocks on water service provision, as Δ returns to zero without delay. M remains at a high level ($M_{fix} = 0.96$) with minimal response to shocks. This indicates high responsiveness, as M has sufficient capacity to respond to shocks while remaining high at all times. Table 5 presents the input parameters and numerical solution for this scenario (rows labeled 'current scenario'), model parameters are listed in the column labeled 'public' and numerical results in column 'low risk'. Figure 2(d) represents the high risk, low robustness scenario for total services (including community adaptation) and figure 2(f) for public services, only. In the latter, the fixed deficit is relatively high ($\Delta_{fix} = 0.33$), service management is relatively low ($M_{fix} = 0.29$), and the return to these values after shocks is significantly delayed. Repeated shocks gradually increase service deficit and eventually lead to complete failure at $t = 74$. Figure 2(e) shows that the system is able to recover from relatively small shocks early in the simulation, but a series of larger shocks and slow recovery from these leads to collapse in the low robustness scenario, even with current risk levels, beginning around $t = 930$ when repeated shocks lead to system failure at $t = 969$. Such a 'worst case scenario' shows how the interplay of a few shortcomings in the different SETS elements of the water supply system could ultimately lead to a complete or near failure of services, as experienced by other cities in the past (e.g. Cape Town, South Africa). Thus, the highly interconnected nature of the NYC SETS underlines the potential for a small number of variables to drive system-wide failure. In such a case, households would need to adapt by activating community capital, finding ways of coping with the deficit of public services, as shown in the scenario in figure 2(d). Here, community adaptation reduces the total deficit to $\Delta_{fix} = 0.12$ and increases M_{fix} to 0.66, accelerating service recovery after shocks, and avoiding system collapse. The input parameters and numerical results corresponding to the time series in panels 2(c), (d), (e) and (f) are shown in table 5 (for data shown in panels 2(g) and (h) see SI).

Figures 2(g) and (h) illustrate the sensitivity of the system to a loss of robustness and security, respectively. Panel (g) shows a scenario with low robustness ($RP = 0.31$), while security is maintained at current levels ($CP = 1.02$). Here, even in a situation of relatively low shock occurrence and high security with a relatively low stable state service deficit level of $\Delta_{fix} = 0.19$, the loss of robustness prevents recovery from shocks. A gradual collapse of the system occurs with complete failure at $t = 352$. This scenario is also characterized by the existence of two non-trivial equilibria, however the low service equilibrium ($\Delta_{fix} = 0.35$) is unstable (see SI for direction field and phase diagram). Panel (h) shows the effect of a loss of security ($CP = 0.66$), alone, while robustness is maintained at current levels ($RP = 0.83$). Such a situation could occur in the case of a shift in the climate regime that would significantly reduce water availability to a level of 50 $m^3\,cap^{-1}\,y^{-1}$ (all else unchanged). Here, the model maintains services at a relatively high level ($\Delta_{fix} = 0.06$), and while shock impact is high, recovery is fast due to the high levels of robustness. Thus, the model shows a high sensitivity to the loss of robustness, and a low sensitivity to the loss of security, alone. This is confirmed by further investigating model response to a further reduction of security and increase of robustness ($CP = 0.31$, $RP = 1$), which produces comparable results ($\Delta_{fix} = 0.14$, fast recovery from shocks). In the real world, such a situation is unlikely, in particular in the current context and under current urban water management paradigms. However, we can imagine a case with high robustness levels, characterized, among others, by the system's adaptability and the capacity to innovate, that allows a transformation from imported supply (e.g. large reservoirs) and centralized piped distribution network to a largely decentralized system, in which rainwater is harvested and water is reused and recycled locally. Thus, the combination of high robustness, low security and resulting high levels of 'services' could be explained. However, such a system would best be described by alternative metrics to quantify water supply security.

4. Discussion and conclusions

We evaluate NYC water supply security and resilience by quantifying the system's social, ecological, and technological capitals, by which we confirm the current high levels of urban water supply services in NYC. The city has substantially reduced direct per capita water demand over the past decades, however, as we showed here, several other sensitive areas exist that could lead to a slow degradation of robustness and a partial failure of water supply services. In particular, more frequent and severe shocks and disturbances caused by an increase in different types of hazards could pose risks to the city's water services in the future, as the rate of adaptation is outpaced by the rate of degradation caused by more frequent and severe shocks. We demonstrate this by developing a plausible scenario that includes the increased occurrence of shocks, and small losses in robustness, which leads to a significant reduction of water service performance and slow recovery from shocks due to a lowered ability to respond to larger and more frequent disturbances. This scenario shows that the nature of complex SETS interactions in NYC's water system has the potential for a small number of variables to drive system-wide failure. Should such a scenario become reality, it would require considerable adaptive response at the household level, underlining the need to support household level adaptive capacity in current NYC resilience planning. A scenario of water insecurity is unlikely to occur in isolation: As climate change impacts intensify, the likelihood of simultaneous disruptions in several urban services increases, including energy supply, wastewater discharge, transportation, and ICT services, which would have serious consequences for wellbeing in the city.

Our model and the CPA framework show how low levels of security can be compensated in a system that exhibits high levels of robustness. The low sensitivity to an isolated loss of security (with high robustness levels) observed in our model provides grounds for questions about future water supply paradigms and how to evaluate their security conditions and mid- to -long-term resilience dynamics. High levels of robustness can prove more important than high levels of security (capital availability), as the former equips the system with flexible and adaptive functions that allow the provision of services despite low levels of capital availability.

The aggregate response that our model simulates has shown to be a good approximation of the overall system behavior. In order to increase SETS service security and resilience urban managers need to design targeted interventions into the availability and robustness of each of the capitals. Thus, future research should aim to collect detailed time-series data that would allow the development of a mechanistic coupled systems model to help understand the interactions and feedbacks between the five capitals, i.e. the social, ecological and technological subsystems, in producing urban water supply security and resilience to shocks.

The implementation of infrastructure and institutions increases security and resilience, and enables the steady flow of resources to urban areas by reducing the natural variability that is due to environmental forcing (e.g. flood and drought cycles) [69]. However, this mediation process, which buffers natural variability, an indicator associated with resilience [10, 70], also dampens potential early-warning signals of critical transitions [71, 72]. This can lead to a false sense of security, and a phenomenon known as robustness-fragility tradeoffs [69, 73]. The effect (termed the 'levee effect' in socio-hydrology [70]) has been shown for flood protection, where the elimination of small flood disturbances reduces vigilance and preparedness to deal with the consequences of floods when they do occur [74]. Similarly, while unconstrained water availability leads to profligate water use, cities with intermittent water supply systems prompt households to save water, to maintain storage capacities for bridging supply gaps, and provide grounds for the emergence of alternative supply systems [75]. These provisions act as buffers during frequent supply interruptions. As disturbances become less frequent, the preparedness to deal with shocks degrades, which can have catastrophic consequences in the case of unexpected extreme events.

However, the joint development of security and resilience is a requirement for the reliable provision of urban services (i.e. the reduction of variability), which in turn are necessary for the efficient functioning of many societal and technological urban processes. Future research should investigate whether and how security and resilience can be mutually strengthened without producing robustness-fragility tradeoffs. Furthermore, lessons learned in the field of robustness-fragility tradeoffs could motivate future research to better understand to what degree, and at what scale (e.g. household or city) variability in urban resource supply should be managed. Our results on the significance of system robustness, relative to security/capital availability indicates points for future reflection. The updated, streamlined CPA method, our findings and these future reflections have relevance not only for NYC, but for urban water supply systems around the world, which are, or will be in the future, facing the intersecting challenges of climate change, urbanization, and the complexities of urban SETS associated with a globalized society.

Data availability statement

All data that support the findings of this study are included within the article and supplementary files.

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