Urban Water Security Dashboard: Systems Approach to Characterizing the Water Security of Cities

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Abstract: Urban water security is a major concern in the context of urbanization and climate change. Water security goes beyond having good infrastructure or good governance. Systems thinking can help in understanding the mechanisms that influence the long-term water security of a city. Therefore, we developed a dashboard of 56 indicators based on the pressure-state-impact-response (PSIR) framework. We applied the dashboard to ten cities to capture different characteristics of their water security and ranked the cities based on their overall water security index score. We found the highest levels of water security in wealthy cities in water-abundant environments (Amsterdam and Toronto), in which security is determined by the ability of the city to mitigate flood risks and the sustainability of hinterland dependencies for water supply. The lowest security was found in developing cities (Nairobi, Lima, and Jakarta). Here, the combination of large socioeconomic pressures (e.g., rapid population growth, slums, low GDP, polluting industries) and an inadequate response (weak institutions, and poor planning and operational management) leads to inappropriate fulfilment of all functions of the urban water system. **DOI: 10.1061/(ASCE)WR.1943-5452.0000997.**

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Introduction

Urbanization and climate change lead to an increased need for studying water management on the urban scale. While in the 1950s only 30% of the world's inhabitants lived in cities, by 2007 this percentage had grown to over 50%. It is expected that by 2050, two-thirds of the world population will be urban dwellers (UN 2014). In many cases, the fast rate of urbanization is exceeding the capacity of governments to respond, leading to a variety of water-related problems, such as inadequate water supply, lack of sanitation, failing stormwater management, and ecosystem degradation (Narain et al. 2013; Sadoff et al. 2015; Varis et al. 2006). At the same time, climate change is exerting increasing pressure on urban water systems by, for example, aggravating flood hazards due to rising sea levels (Hallegatte et al. 2013) and increasing the frequency of prolonged dry periods (Isler et al. 2010).

The aim of this study is to characterize the water security of cities by developing and applying a new urban water security dashboard. We take a systems perspective on urban water security by developing a dashboard of indicators based on the pressure-state-impact-response (PSIR) framework (EEA 1999). We use this to develop a scoring framework to characterize, compare, and rank the water security of ten cities. We not only consider the fulfilment of the functions of a city's water system and its proper governance but also consider what comes before: the state of the system and the challenges the system faces. Although the focus is on urban water systems, we explicitly consider the water dependency of a city on its hinterland as well.

Water security is an emerging concept that adds value to the urban water management discourse (Bakker 2012). In water management studies, the concept complements the dominant integrated water resources management (IWRM) paradigm (Bakker and Morinville 2013; Cook and Bakker 2012). Related concepts are things like sustainable, resilient, adaptive, climate proof, and robust urban water management; although these terms have much in common, they emphasize different aspects of urban water management. IWRM is concerned with the process of water management, while water security relates to an important goal of water management. IWRM emphasizes that water management is a compromise between economic development, social equity, and ecological integrity. The term *security* implies certain thresholds beyond which a compromise is unacceptable (Bakker and Morinville 2013). Water security is framed in different ways; for an in-depth review of different perspectives, see Hoekstra et al. (2018). Some scholars have adopted a broad understanding of water security, which resembles the scope of IWRM (e.g., GWP 2000), while others have focused on risk (Garrick and Hall 2014; Grey et al. 2013; UN-Water 2013). The latter approach defines water security as an accepted level of water risk or the other way around—the absence of intolerable water risks (Hall and Borgomeo 2013; OECD 2013). By defining risk as the combination of hazard, exposure, and vulnerability, this approach fits best in relation to urban flood risks (Hallegatte et al. 2013). Another dominant, albeit more narrow, framing defines water security as matching water demand and supply (Brears 2017;

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Chang et al. 2015). Although widely accepted, such an understanding of water security overlooks other security aspects, such as flood risks and the environmental status of ecosystems. Following Cook and Bakker (2012) and Zeitoun et al. (2016), we adopt a broad and integrative understanding of water security, which covers the commonplace problems of urban water management: too little, too much, or too dirty water (OECD 2016).

Many interrelated mechanisms play a role in fulfilling the functions that make a city water secure; these mechanisms can be clarified using systems thinking (Barendrecht et al. 2017; Srinivasan et al. 2017). Basic criteria, such as meeting urban water demand by adequate supply or treating wastewater to allowable levels, have to be met, while increasing pressures, changing conditions, and governance all influence a city's water security (Bakker and Morinville 2013; Koop and van Leeuwen 2015a; Milman and Short 2008; Rijke et al. 2013; Van de Meene et al. 2011). Given this complexity, we underscore the need to adopt a systems perspective on urban water security (see also Romero-Lankao and Gnatz 2016). The PSIR scheme is a commonly used framework for systems analysis that structures indicators that describe dynamic environmental systems (OECD 1993; EEA 1999; Pires et al. 2016; Sekovski et al. 2012). The PSIR framework schematizes the urban system dynamics using four stages: pressure (P), state (S), impact (I), and response (R). System pressures change the state of the system, which in turn has an impact on system functions, which then evokes societal and governmental responses. The responses can intervene at the level of pressures, states, and impacts. The framework has been successfully applied at the urban level to study environmental problems in general (da Costa Silva 2014; Zebradast et al. 2015), water problems specifically (Chen et al. 2015; Hazarika and Nitivattananon 2016), and holistic water management challenges (Liu et al. 2012; Sun et al. 2016).

The benchmarking and ranking of cities is being seen more and more frequently, both in the scientific literature and beyond (Arribas-Bel et al. 2013; Kılkış 2016). Ranking is typically done along a number of criteria; examples include urban sustainability indices like the green city index by Siemens (2012) or the index by Phillis et al. (2017). There are a large number of water (security) indicators, although few of them specifically focus on urban water security. Examples of dedicated indicators for urban water management are the sustainable cities water index by Arcadis (2015) and the city blueprint by Van Leeuwen et al. (2016). However, these rankings either seem to lack a sound theoretical foundation (e.g., the sustainable city water index) or have a predominantly performance-oriented approach (e.g., the city blueprint). Since ranking appears to appeal to policy makers, we ranked selected cities based on their overall score on the different indicators of the PSIR framework in order to arrive at a quantitative measure for urban water security [see Yang et al. (2012) for a catastrophe theory approach and Jensen and Wu (2018) for an approach highlighting the time dimension of water security]. Yet, with indicator development and ranking always being subject to some degree of subjectivity, the richness of understanding lies behind the overall scores, that is, in the scores per indicator and indicator category.

Method

Using the PSIR framework, we constructed a dashboard of indicators that we then applied in order to score ten selected cities. Indicator scores were aggregated to a water security (WS) index that we used to rank the cities. We then studied the coherence between indicators' scores on different levels of aggregation (called tiers) to obtain insight into the system dynamics.

First, we developed 56 indicators, which cover all relevant aspects of the PSIR framework for urban water security and together form the dashboard. Via three steps of aggregation, the dashboard indicators (tier 1) were aggregated to a water security index score (tier 4), as outlined in Table 1. Indicators (tier 1) were grouped into categories (tier 2), which in turn made up the respective stages of pressure, state, impact, and response (tier 3), which combined into

Table 1. Overview of indicators (tier 1) per category (tier 2) and P, S, I, or R index (tier 3) with their main methods and primary source of data

Code	Name	Method	References
1000	**PRESSURE INDEX**	[Average (1100, 1200) − 1] × 25	—
1100	**Environmental pressures**	Average (1110, 1120)	—
1110	*Water scarcity*	Average (1111, 1112)	—
1111	Annual precipitation and variability	Search procedure, global study	Peel et al. (2007)
1112	Freshwater scarcity around city	Global study	Mekonnen and Hoekstra (2016)
1120	*Flooding*	Average (1121, ..., 1125)	—
1121	Rainfall intensity and variability	Search procedure, global study	Peel et al. (2007)
1122	Storm surge hazard	Global study, search procedure	Muis et al. (2016)
1123	Tsunami hazard	Global study, search procedure	Peduzzi et al. (2009)
1124	Expected SLR by 2100	Global study	Church et al. (2013)
1125	Area below MSL +1 m and subsidence	Search procedure, global study	USGS and Google (1996)
1200	**Socioeconomic pressures**	Average (1201, ..., 1208)	—
1201	City population	Search procedure	—
1202	Population growth	Search procedure	—
1203	GDP (PPP)	Search procedure, national data	World Bank (2017)
1204	Slums	Search procedure, national data	UN (2015)
1205	Domestic water use	City data, search procedure	IB-NET (2017)
1206	Water footprint of consumption	National data	Mekonnen and Hoekstra (2011)
1207	Water-intensive industries	Search procedure	—
1208	Condition upstream watershed	Search procedure	—
2000	**STATE INDEX**	[Average (2100, ..., 2500) − 1] × 25	—
2100	**Water quantity**	Average (2101, 2102, 2103)	—
2101	Supply continuity of reservoirs and lakes	Search procedure, global study	Global Reservoir and Dam Database (Lehner et al. 2011)
2102	Dependency on overexploited aquifers	Search procedure, global study	Gleeson et al. (2012)
2103	Local groundwater drawdown	Search procedure	—

Table 1. (*Continued.*)

Code	Name	Method	References
2200	**Water supply infrastructure**	Average (2201, 2202)	—
2201	Coverage and leakage of water supply system	Search procedure, city data	IB-NET (2017)
2202	Continuity and quality of water supply	Search procedure, city data	IB-NET (2017)
2300	**Flood protection infrastructure**	Average (2301, 2302, 2303)	—
2301	Coastal flood protection infrastructure	City data, search procedure	Hallegatte et al. (2013)
2302	River flood protection infrastructure	City data, search procedure	FLOPROS (Scussolini et al. 2016)
2303	Stormwater drainage infrastructure	Search procedure	—
2400	**Sanitation infrastructure**	Average (2401, 2402)	—
2401	Coverage and leakage of sewer system	Search procedure	—
2402	Adequacy of wastewater treatment	Search procedure	—
2500	**Water quality**	Average (2501, ..., 2505)	—
2501	Surface water quality	Search procedure	—
2502	Polluted sediments	Search procedure	—
2503	Garbage in surface water	Images	Panoramio (Google 2016)
2504	Groundwater quality	Search procedure	—
2505	Salt water intrusion in groundwater	Search procedure	—
3000	**IMPACT INDEX**	[Average (3100, ..., 3600) − 1] × 25	—
3100	**Water supply dependencies**	Average (3101,3102)	—
3101	Conflicts over water supply	Search procedure	—
3102	Sustainability of urban water footprint	National data	Mekonnen and Hoekstra (2011)
3200	**Water supply**	Average (3201, 3202)	—
3201	People with adequate water supply	National data	WHO and UNICEF (2015)
3300	**Flood protection**	Average (3301, 3302, 3302)	—
3301	Coastal flooding	Global study, search procedure	Dartmouth Flood Observatory
3302	River flooding		Database (Brakenridge 2016)
3303	Stormwater flooding		
3400	**Sanitation**	Average (3401, 3402)	—
3401	People with adequate sanitation	National data	WHO and UNICEF (2015)
3402	Water-associated diseases	Search procedure	—
3500	**Ecology**	Average (3501)	—
3501	Ecological quality of urban water	Search procedure	—
3600	**Aesthetic**	Average (3601)	—
3601	Water image of city	Images	—
4000	**RESPONSE INDEX**	[Average (4100, ..., 4300) − 1] × 25	—
4100	**Institutional framework**	Average (4101, ..., 4105)	—
4101	Clarity of roles and responsibilities	Questionnaire[a]	—
4102	Horizontal coordination		—
4103	Vertical coordination		—
4104	Corruption		—
4105	Accountability		—
4200	**Planning**	Average (4201, ..., 4205)	—
4201	Access to data and information	Questionnaire	—
4202	Financial resources		—
4203	Effectiveness of disaster management		—
4204	Strategic planning		—
4205	Degree of public participation		—
4300	**Operational management**	Average (4301, ..., 4304)	—
4301	Effectiveness of water supply management	Questionnaire	—
4302	Effectiveness of sanitation management		—
4303	Effectiveness of flood protection management		—
4304	Effectiveness of environmental and ecological management		—

Note: MSL = mean sea level; PPP = purchasing power parity; SLR = sea level rise; bold text = tier 2; capitalized, bold text = tier 3; City data = city-specific data obtained from databases and indices; Global study = global analysis of a certain phenomenon, e.g., on river basin or national scale; National data = data on national level; Search procedure = search procedure with prescribed keywords to identify credible sources via (a) Scopus, (b) Google Scholar, and/or (c) Google search; Images = classification of images identified via a prescribed procedure; and Questionnaire = consultation of experts on city-specific situations using a questionnaire. For a detailed description of all methods, see the Supplemental Data.
[a]See the Supplemental Data for the number of respondents per city.

the water security index score (tier 4). Pressures (tier 3) were defined as the basic factors, root causes, and trends that influence and determine the state of the urban water system (Pires et al. 2016; citing EEA 1999; WWAP 2006). We distinguished between environmental (natural resource) and socioeconomic pressures (Hoekstra 1998; OECD 2016; Van Leeuwen and Chandy 2013). The two main environmental pressure categories (tier 2) were water scarcity and flooding (Fig. 1). Socioeconomic pressures refer to the claims a city puts on available resources. This category included indicators for the size and growth of a city and the economic development level, water consumption, and industrial activities in the city and its surroundings. State (tier 3) was defined as the current physical properties of the natural and infrastructural elements of the urban water system (Pires et al. 2016). State categories (tier 2)

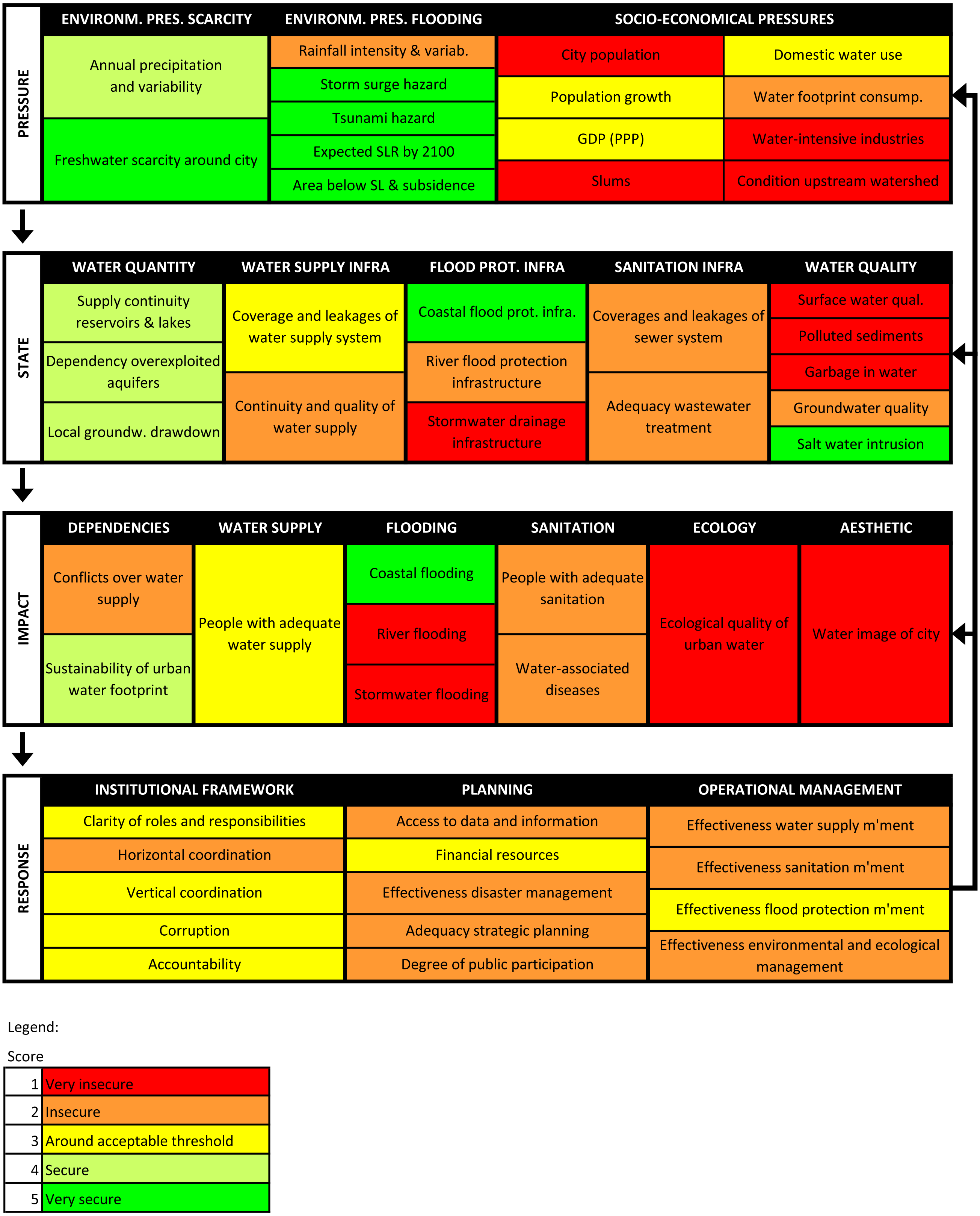

Fig. 1. Urban water security dashboard for São Paulo, tier-1 level. See the Supplemental Data for all dashboards scored on the indicator (tier-1) level.

were: water quantity, water quality, the state of urban water supply infrastructure, the state of flood protection infrastructure, and the state of sanitation infrastructure. Impact (tier 3) was defined as the effects of the system state on functions to be fulfilled by the urban water system (Pires et al. 2016). We distinguished the following impact categories (tier 2): dependencies, water supply, flooding, sanitation, ecology, and aesthetics (see also Brown et al. 2009). Under dependencies, we accounted for the risks associated with the supply of drinking water and the supply of water-intensive goods from the hinterland of the city (Hoekstra and Mekonnen 2016; McDonald et al. 2014; Schyns et al. 2015). Response (tier 3) refers to attempts by human actors to "prevent, compensate, ameliorate, or to adapt to the impact of the changes in the state" (Pires et al. 2016). We assessed the adequacy of the response in three categories (tier 2): institutional framework, planning, and operational management. The full dashboard, with all indicators and categories, is shown in Fig. 1. A description of each of the 56 indicators can be found in the Supplemental Data, in which we also explain the rationale of the indicators and discuss their limitations.

Next, cities were scored for each indicator within the dashboard. This indicator score represented the most disaggregated level (tier 1). We assigned indicator scores on a 1–5 point scale, based on publicly available data and literature for the indicator at hand. For the response indicators, we asked experts to fill out a questionnaire on city-specific governance settings. Someone was considered an expert if he or she had either worked in the urban water sector (in a policy-related position) or had studied the city-specific governance setting. We used a minimum of three expert responses, with an average of 4.4 responses for each city. Detailed methods to assign indicator scores are described in the Supplemental Data.

After assigning scores, we aggregated the tier-1 indicator scores of the dashboard to scores per category (tier 2). We characterized cities based on similarities in these category scores, as shown in Fig. 3. We further aggregated the tier-2 scores to indices at the P, S, I, and R levels (tier 3). Finally, the four tier-3 indices were further combined into one water security index (tier 4), which determined the final ranking of the selected cities. Aggregation from each tier to the next was done by taking the arithmetic mean. The tier-3 and tier-4 indices were first normalized on a 0–100 score (Table 1). Ten major cities (in terms of economy and size) were selected to represent differences in development level, climate, and geographical location, while also considering data availability. The ten selected cities are listed in Fig. 2.

Results

We present the results in three steps. First, the ranking obtained based on the water security index (tier 4) is given, together with the underlying city scores for the indices for P, S, I, and R (tier 3). Second, we group cities based on resemblances between the dashboard scores (tier 2 and 1) and discuss the typical dynamics per group. Third, we obtain further insight into the system dynamics that lead to a certain level of water security by looking specifically at water supply, flood protection, and water quality.

Rank	City name	WS-index	P-index	S-index	I-index	R-index
1	Amsterdam	82	61	91	88	88
2	Toronto	77	72	86	75	76
3	Singapore	74	67	85	74	68
4	Dubai	60	40	56	66	77
5	Beijing	52	51	48	46	63
6	Hong Kong	50	50	59	52	40
7	São Paulo	41	65	39	26	35
8	Nairobi	35	61	23	14	40
9	Lima (Peru)	32	40	17	29	41
10	Jakarta	30	49	11	16	43

Fig. 2. Ranking of cities based on their water security index (tier 4), with scores for the underlying pressure, state, impact, and response indices (tier 3). Scores can range between 0 (worst) and 100 (best).

Overall Ranking

Fig. 2 shows the rankings of the cities based on water security index (tier 4) with their scores for each of the PSIR indices (tier 3). The top three were Amsterdam, Toronto, and Singapore, and the lowest ranking were Nairobi, Lima, and Jakarta. In the middle were Dubai, Beijing, Hong Kong, and São Paulo.

Cities experience various levels of pressure. The extent to which this pressure affects state and impact differs; these differences can largely be explained by the adequacy of the response. An adequate response to (partly inevitable) pressures is key to preventing the water system state from worsening and to appropriately fulfill functions of urban water to avoid undesirable impacts. In other words, a low P index score (high water risk because of high pressure) in combination with a low R index score will result in low S and I index scores as well. However, a low P index score may be compensated for by a high R index score, so that the S and I index scores are not affected. Evidently, it is an advantage to be under relatively low-pressure conditions; the top three cities in terms of WS index scored above average on the P index. Yet a high P index score does not typically lead to proper fulfilment of urban water functions—that is, a high I index score. For example, São Paulo and Nairobi scored high on the P index, but low on state and impact. The decisive factor in attaining high S and I scores seems to be the adequacy of the response rather than a given level of pressure. Dubai shows that a high I index score can be obtained even under a low P index score provided there is an adequate response. In contrast, the example of Lima shows that, when a low P index score is paired with an inadequate response, both the state and impact indices are low. Overall, we found that system pressures can be partly mitigated by an adequate response, so that these pressures do not affect state and impact that much. However, the highest level of water security is obtained if pressures are low and response is adequate.

System Dynamics in Different Types of Cities

Comparison of the dashboards of different cities reveals notable similarities between cities. Some cities have comparable stories; their indicator scores followed roughly the same pattern and represented similar system dynamics. We distinguished five different city stories, as summarized by the category level (tier 2) dashboards in Fig. 3. Indicator level (tier 1) dashboards can be found in the Supplemental Data.

Amsterdam and Toronto: Water-Abundant and Wealthy

Amsterdam [Fig. 3(a)] and Toronto topped the ranking and their indicators show similar patterns. These patterns are likely representative for wealthy cities in water-abundant environments. Concerning pressure, moderate rainfall is equally distributed over the year. However, lakes, rivers, and the sea pose substantial flood hazards. Socioeconomic conditions are favorable: the cities have a high gross domestic product (GDP), no slums, and little polluting industry. The state of the systems in terms of water quantity is good; available water resources are not overexploited. Water supply and sanititation infrastructure is good, and flood protection infrastructure is sufficient to mitigate flood hazards. Water quality remains a point of concern. Concerning impact, water supply and sanitation are adequate, but flood risks can be reduced and ecology improved. In addition, the good state of the systems contributes to the aesthetic function of water in the city. The governments' responses are adequate, with horizontal (cross-sectoral) coordination being the only weakness.

Amsterdam had a higher overall index because it scored higher for flood protection, water quality, and response. Moreover, Toronto

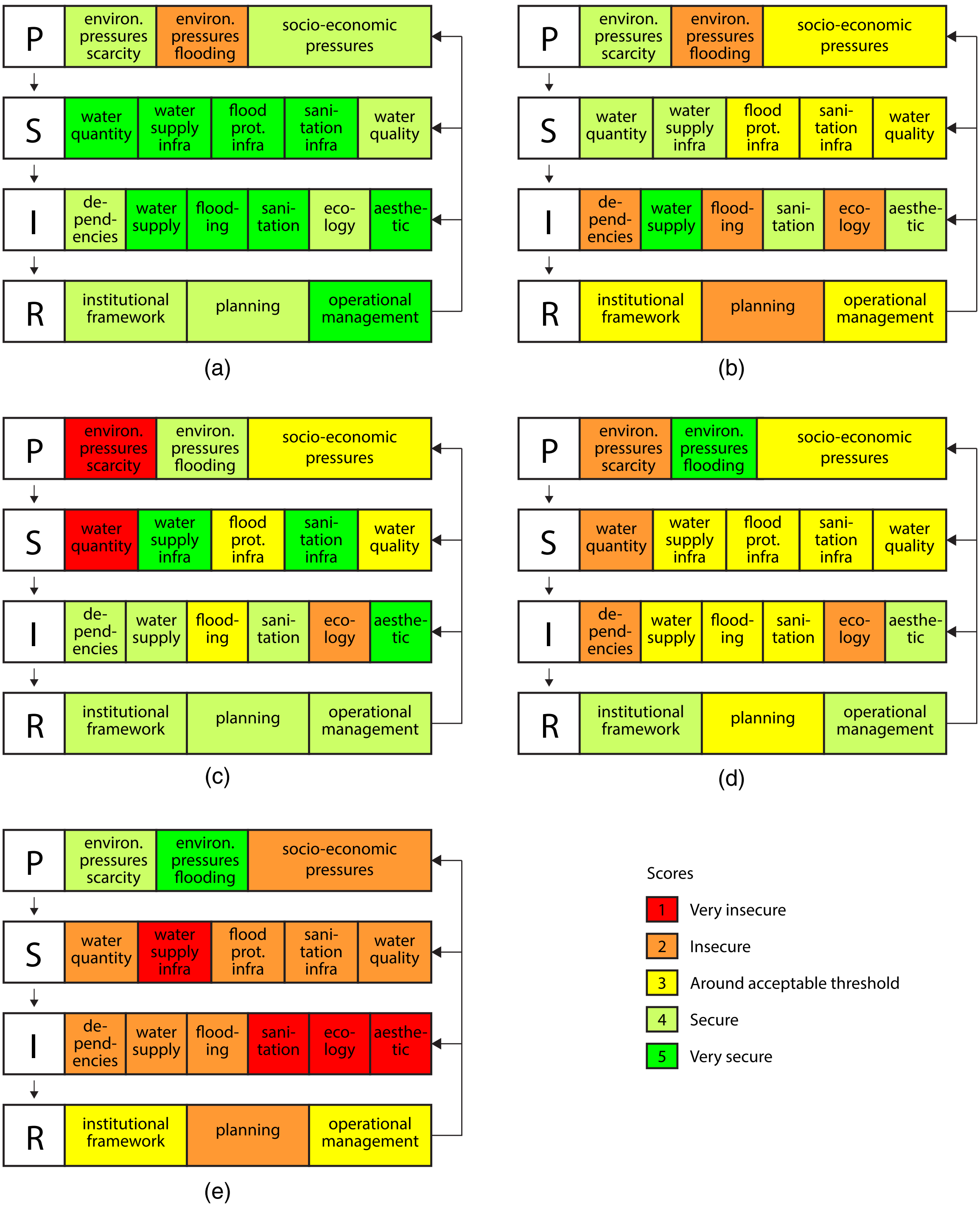

Fig. 3. Category-aggregated dashboards (tier 2) showing system dynamics of five (arche)typical cities: (a) Amsterdam: water-abundant and wealthy; (b) Hong Kong: water-abundant but subtropical and dependent; (c) Dubai: wealthy and desertlike; (d) Beijing: megacity in emerging economy; and (e) Nairobi: developing city. The variation in individual indicator (tier 1) scores (especially socioeconomic indicators of pressure) is obscured by the aggregation to category scores (tier 2) depicted here. Fully specified dashboards, showing indicator level scores, can be found in the Supplemental Data.

had a high domestic water use (>300 L cap^{-1} day^{-1}; Amsterdam 115 L cap^{-1} day^{-1}) and a large water footprint of consumption (around 6,400 L cap^{-1} day^{-1}; Amsterdam 4,000 L cap^{-1} day^{-1}), both of which reduce Toronto's P index score. Toronto could surpass Amsterdam in the ranking if it improved on these indicators, because its environmental setting is more favorable. In Toronto, only a small strip of land along the coast of Lake Ontario is threatened by storm surges, whereas in Amsterdam a major part of the city is at or around sea level, at risk of storm surges from the North Sea, and threatened by sea level rise. In general, the water security of a water-abundant, wealthy city is determined by its ability to mitigate flood hazards. The maximum level of security can be reached in cities facing the lowest pressures, that is, with the highest P indexes.

Singapore and Hong Kong: Water-Abundant and Wealthy, but (Sub)Tropical and Dependent

Ranking third and sixth respectively, Singapore and Hong Kong [Fig. 3(b)] have a similar story despite a substantial difference in WS index. Located on islands in a (sub)tropical climate, these cities host ports that are among the busiest in the world. Water quality has deteriorated due to marine and residential emissions, which impacts urban ecology. Both cities receive high rainfall (2,000–3,000 $\mathrm{mm\,y^{-1}}$), which favors water availability but challenges the urban drainage system. In contrast to Amsterdam and Toronto, supply from local groundwater, reservoirs, and lakes is limited. This makes Singapore and Hong Kong dependent on water resources beyond their jurisdictions, which has potential for conflicts about hinterland dependencies. To rely less on water imports, Singapore and Hong Kong have turned to extensive rainwater harvesting, water reuse, and desalination technology.

Singapore scored lower on the category hinterland dependencies, as it partly depends on imports from another country (Malaysia), while Hong Kong is a special administrative region of the People's Republic of China. Singapore leads the transition toward independence in water supply. Response in Singapore is better, and the city is wealthier; these factors partly explain the better state of the water supply, sanitation, and flood infrastructure as compared to Hong Kong. The sewer system and wastewater treatment in Hong Kong are less advanced, inducing larger water quality deterioration. Hong Kong—hit by five typhoons a year on average—suffers more from stormwater flooding and ecological degeneration, which also negatively impact its water image.

Wealthy and Desertlike: Dubai

Water scarcity puts a large environmental pressure on the water supply of Dubai [Fig. 3(c)]. The city receives a mere 100 mm of rainfall per year, challenging the supply of drinking water. The city is prosperous, of moderate size, growing quickly (6.6% per year), and its domestic water use is among the highest in the world (>500 $\mathrm{L\,cap^{-1}\,day^{-1}}$). A natural freshwater buffer is absent, and the limited groundwater resources are overexploited. However, most people have adequate water supply, albeit through energy-consuming desalination technology, which accounts for over 99% of total water supply. The city has difficulty keeping up its sanitation infrastructure with its rapid urban growth. Moreover, occassional rainfall events cause problems because the drainage infrastructure is poor. But in general, functions of the urban water system are adequately fulfilled and the city maintains a positive water image. The governance response is adequate; this, together with its high GDP, seems to explain the proper fulfillment of water system functions in this challenging environment. Apparently, it is possible to build a well-performing city in the desert, but at a price: the supply system is vulnerable and energy use is substantial.

Beijing and São Paulo: Megacities in Emerging Economies

Beijing and São Paulo [Fig. 3(d)] ranked fifth and seventh, respectively, and their story represents megacities in emerging economies (see Li et al. 2015 for an extensive discussion). The main system pressure stems not so much from the environment but rather from socioeconomic conditions. São Paulo has 12 million inhabitants, and Beijing's population has surpassed 20 million. Each inhabitant consumes around 200 L of drinking water a day. Furthermore, an extensive industrial sector is present, including water-intensive and polluting industries (such as textile, metallurgical, and petrochemical industries). Additionally, industrialization, urbanization, and agriculture in upstream catchments reduce river discharge to these cities and cause water pollution. The environment is not particularly prone to scarcity and flood pressures, but the cities' claim on the available resources exceeds availability. This leads to overexploitation of local water resources and deterioration of water quality. Water supply can only be guaranteed by water imports from distant sources, which potentially incurs conflicts with other water users. In China, water is transported to Beijing from sources over 1,000 km away via the south-north water transfer project. In São Paulo, water levels in reservoirs frequently reach critical levels. This leads to conflicts with other users competing for the same water. In both cities, infrastructure is insufficient in some sections. Rainstorm events cause inundations of up to 1 m locally, disrupting traffic. Ecosystems are heavily compromised and the water image is negatively affected. Comparing Beijing and São Paulo underscores the decisive importance of an adequate response. Although Beijing is larger in terms of population size and more water-scarce than São Paulo, urban water functions are fulfilled better. This seems to result from more adequate water governance in Beijing. The adequacy of water governance in a megacity is critical to ensure water security within the city proper and to warrant the environmental status of its hinterland (cf. Varis et al. 2006).

Nairobi, Jakarta, and Lima: Developing Cities

At the bottom of the list, were three cities under differing environmental pressures but with socioeconomic pressures that are typical of developing countries: the cities have a low GDP, large slums, polluting industry, and unfavorable upstream conditions. Concerning state, the groundwater is overexploited, the water supply infrastructure is insufficient, and water quality is severely deteriorated. On the impact level, none of the water system functions are adequately fulfilled—not even those that lack environmental pressures. Nairobi [Fig. 3(e)], which is neither particularly water-scarce nor facing large flood pressure, still suffers from inadequate water supply, stormwater flooding, and riverine flooding. Lima, with average annual rainfall of no more than 10 $\mathrm{mm\,year^{-1}}$, was recently struck by heavy flash floods and mudslides, which caused several casualties and a disrupted society. Large parts of Jakarta subside 5–10 $\mathrm{cm\,year^{-1}}$ due to excessive groundwater abstractions although the city is in a water-abundant environment. It seems that when a city faces severe socioeconomic pressure, all urban water functions are eventually compromised, regardless of the environmental setting.

System Dynamics of Water Supply, Flood Protection, and Water Quality

In the following sections, we zoom in on the dynamics around water supply, flood protection, and water quality. First, we describe how the pressure of water scarcity affects water supply and hinterland dependencies. Second, we elaborate on how natural conditions can evoke flood impacts and argue that, despite adequate response, a certain level of insecurity will remain. Finally, we show how socioeconomic pressures and sanitation infrastructure influence water quality and relate to ecology.

Water Supply

Cities in water-scarce environments overexploit naturally available resources before turning to unconventional sources or reducing water use. In Lima, Nairobi, and Jakarta, many residents (illegally) withdraw water from local aquifers because the municipal water supply system is unreliable. In Jakarta, this free-riding behavior causes large land subsidence, which in turn aggravates flood hazards. Uncontrolled groundwater withdrawal can also result in lower water tables, increasing pumping costs, saline intrusion, and other problems. In cities facing water scarcity pressures (Dubai, Lima, and Beijing), we observed that municipal water suppliers overexploit local water resources. Cities use two strategies to guarantee water supply when local sources are depleted. First, they "build their way out of scarcity" (McDonald and Shemie 2014) by interbasin transfers from other catchments (Lima, Beijing). Alternatively, they turn to unconventional water sources (Dubai). The first strategy comes at a cost for water users elsewhere; the second strategy is highly energy-consuming (Wen et al. 2017). Interbasin water transfers are usually preferred by policy makers, since they are the cheapest and easiest option. Unconventional sources are used when hinterland dependencies incur large conflicts or when no water resources are available in a city's surroundings. Wealthy but dependent cities such as Singapore and Hong Kong mimic this pattern. In these cases, conflicts over water supply dependencies are leading to a transition toward unconventional sources of water supply. This transition is usually accompanied by increased attention to reduction of domestic water use.

Water abundant cities may still be at risk because of the imported water risk associated with unsustainable hinterland dependencies. In most investigated cities, the unsustainable fraction of the urban water footprint was greater than 60%. This implies that the majority of consumed goods are produced in areas where the actual water footprint exceeds the maximum sustainable water footprint. Consequently, the current way of producing these goods cannot be sustained. Notably, this category of water insecurity is often opposite to other categories on the impact level. São Paulo and Jakarta, which scored below average on all other functions on the impact level, had the best scores on sustainability of water footprint. The other cities scored lower on this security aspect, despite their better overall impact scores. Even Amsterdam and Toronto, located in water-abundant areas, have an unsustainable fraction of the water footprint between 40% and 60% because they import goods from unsustainable source regions. Reducing this unsustainable fraction of the urban water footprint would contribute to their urban water security. Previously, we observed that, for drinking water, cities tend to overexploit the locally available resources and that conflicts make them adopt unconventional water sources and reductions in water use. Analogously, cities overexploit their hinterland via virtual water dependencies as expressed by the unsustainable fraction of the urban water footprint. These dependencies may lead to conflicts in the future, because freshwater is becoming increasingly scarce globally (Kummu et al. 2016; Mekonnen and Hoekstra 2016). Enormous quantities of virtual water—embedded in consumed products—are consumed in cities (cf. Hoff et al. 2014; Paterson et al. 2015), resulting in overexploitation of water resources elsewhere. Again, similar to drinking water dependencies, cities will increasingly be held accountable for their claims on limitedly available resources. Although virtual water supplies to cities differ from drinking water supplies, both types of dependencies essentially concern increasingly scarce freshwater resources. We expect that, in the near future, the sustainability of urban water footprints will become an important dimension of urban water security.

Flood Protection

Coastal cities below sea level are never fully water secure. Large parts of Amsterdam and Jakarta are below sea level, a pressure that will increase due to rising sea levels and land subsidence. Amsterdam mitigates its storm surge hazard by extensive flood-protection infrastructure. Jakarta's flood pressure is lower, but the state of its infrastructure is worse. In recent history, Jakarta's coastal flood defense was challenged severely by extreme water levels but proved just sufficient to prevent a large-scale disaster. Other cities have been less fortunate, such as New Orleans when Hurricane Katrina struck in 2005 or several towns in Japan that were hit by a tsunami in 2011. The lesson learned is that the essence of water security is that the unexpected always happens. Cities facing significant pressures can mitigate their flood risk to a large extent, but are not—nor will they ever be—as secure as cities that lack such pressures. Pressures must be included in assessments of urban water security, because a pressure may always cause an impact via an unexpected pathway. Coastal cities located above sea level (Lima, Singapore, Dubai, Hong Kong) require less flood-protection infrastructure, although sea level rise puts a pressure on the coastline and offshore land reclamations of even these cities.

Cities in water-scarce environments suffer from stormwater flooding events just as severe as cities in water-abundant regions. Even desert cities like Dubai and Lima recently suffered from disruptive stormwater flood events. Singapore, in contrast, is under the pressure of much heavier tropical rainstorms on a regular basis, but the overall impact of flooding is smaller. This shows that, because of an adequate response, cities can adapt to the environmental pressures that are typical for their environmental setting, whereas unexpected phenomena cause the largest societal disruptions.

Water Quality

A shared conclusion for all cities investigated is that water quality and ecology in cities is unequivocally compromised. Not only in developing cities Nairobi, Jakarta, and Lima, but also in São Paulo and Hong Kong, the quality of groundwater and surface water is severely deteriorated as a result of inadequate sewage systems and insufficient wastewater treatment. The presence of polluting industries also puts significant pressure on the water quality of urban surface waters. In coastal cities, an additional threat originates from maritime pollution (Dubai, Lima), especially in the presence of large ports (Singapore, Hong Kong). Even in Toronto and Amsterdam, where other system functions are adequately fulfilled, water quality and ecological status are compromised (see also Brown et al. 2009). Apparently, the natural environment is being sacrificed for the benefit of other functions (Stewart-Koster and Bunn 2016). In this context, it is telling that the horizontal coordination scores were by far the worst of all response indicators; 35 out of 42 experts scored this indicator as 2 (low) or 1 (very low).

Discussion

The number of investigated cities is too small to cover the whole spectrum of urban water situations worldwide. A larger sample of cities may reveal additional system-dynamic patterns, which would enable alternative or richer characterizations. Uncertainty and subjectivity in indicator scores, emerging from the qualitative interpretation of literature and uncertainty in the quantitative data, underscores the fact that our results should be interpreted with caution. Both the limited number of respondents to the questionnaires and their personal judgment, background, and beliefs about good governance make generalizations precarious. Also, for each aggregation, the underlying scores received equal weight (Table 1). In practice, some urban water functions are prioritized over other functions (Brown et al. 2009), justifying alternative weighting procedures.

The strength of the dashboard using the PSIR framework is that it gives insight into the complex cause-and-effect relations that lead to a certain level of water security. The greatest quality of the PSIR approach according to Sekovski et al. (2012) is "the ability to provide cause-consequence relationships between the anthropogenic activities and complex environmental processes in a descriptive and rather simple way." The drawback is that the choice of indicators leaves room for subjectivity, especially in terms of what causal relations exist between different indicators (Sekovski et al. 2012; Sun et al. 2016). One could, for example, emphasize alternative aspects of water security, such as the cascading impacts of

Table 2. Comparison of the water security index of this study with existing indices

City name	WS index	Sustainable cities water index[a]	Blue city index (city blueprint)[b]
	Scale		
	0–100	0–100	0–10
Amsterdam	82	84	8.4
Toronto	77	80	—
Singapore	74	70	—
Dubai	60	61	—
Beijing	52	62	—
Hong Kong	51	62	—
São Paulo	41	60	—
Nairobi	35	43	—
Lima	32	—	—
Jakarta	30	42	—

[a]Arcadis (2015).
[b]Van Leeuwen et al. (2016).

water-related disasters on critical urban infrastructures. The systems approach could be extended by including the relation of water security to energy use (Kılkış 2016), which is strongly related to the characteristics of the urban water system (Chhipi-Shrestha et al. 2017).

Despite differences in conceptual framing, the rankings obtained by our WS index resembles the rankings in the Arcadis Sustainable Cities Water Index (Table 2). This shows that, although different indices focus on different aspects of urban water management, some cities have an undisputedly better urban water system than others. The largest dissimilarity between our ranking and the Arcadis index is observed for São Paulo, for which the WS index was 19 points lower than the Arcadis index ranking. This is best explained by the low response index in our study, which, through the governance dimension, receives little attention in the Arcadis index. Our ranking overlaps with three megacities covered in the study by Li et al. (2015) (Beijing, São Paulo, and Jakarta), who qualitatively confirm our findings for these cities as outlined in sections titled "Beijing and São Paulo: Megacities in Emerging Economies" and "Nairobi, Jakarta and Lima: Developing Cities." The overlap between our city list and the list of cities evaluated with the revised city blueprint is too small to substantially compare the two, although the similarity between scores for Amsterdam is noteworthy (Table 2). It is interesting to compare the revised city blueprint framework (CBF) and our urban water security dashboard (UWSD), which seemingly aim for the same thing but have different underlying philosophies. We observe four differences: (1) CBF is performance-oriented (Koop and van Leeuwen 2015b), while our UWSD is security-oriented; (2) CBF is primarily designed to enable city-to-city learning, while we seek to understand the nature and dynamics of urban water security; (3) CBF aims at assessing the sustainability of the urban water cycle and is dominated by IWRM terminology, whereas we take our perspective from the water security literature; and (4) the CBF performance-oriented approach ignores some aspects that are critical for urban water security but that have no direct perspective for action by local water authorities. In an earlier version of the CBF, indicators for trends and pressures were included. These were later removed, following the reasoning that it is unfair to compare the IWRM performance of cities that operate in different settings (Koop and van Leeuwen 2015b). From a systems perspective, mapping environmental and socioeconomic pressures is key to understanding overall urban water security. Also, indicators related to water footprint were removed from the CBF because there was a lack of action perspective for local water authorities; the water imports and exports of a country are highly dependent on many socioeconomic processes and national and global trends on which local water authorities have a negligible influence (Koop and van Leeuwen 2015b). From a security perspective, external water dependencies can be an important source of water-related risks (Hoekstra and Mekonnen 2016; Schyns et al. 2015), and the fact that these are beyond the control of local authorities is a reason for even more concern. However, combining the trends and pressure framework (Koop and van Leeuwen 2015a) and the recently introduced governance capacity framework (Koop et al. 2017) with the city blueprint framework enables a study of urban water management that resembles a system-dynamic approach. The value of a system-dynamic approach to water security is not merely in the resulting dashboards or rankings themselves but rather in a way of thinking that includes factors from the whole cause-and-effect chain in the assessment of water security. It can help city planners and managers gain insight into the water security of their cities compared to other cities located in similar environmental or socioeconomic conditions.

Conclusions

We set out to create insight into the system dynamics of urban water systems that lead to a certain level of water security. The highest level of water security was found in water-abundant and wealthy cities such as Amsterdam and Toronto. Their degree of security is mainly determined by their ability to mitigate flood hazards, although they will never be fully secure as long as the risk of flooding exists. Moreover, even such water-abundant cities are subject to an imported water risk associated with unsustainable hinterland dependencies on drinking water and water embedded in goods consumed. We further found that a desert city (such as Dubai) may reach a reasonable level of security but at the cost of energy consumption in desalinating sea water. However, before turning to unconventional sources and reducing water use, cities—especially those located in water-scarce environments—overexploit locally available resources. Megacities in emerging economies suffer from water insecurity even when located in favorable environments because their claim on the available resources is simply too large. The largest insecurities were found in cities in developing countries, for which all water system functions are inadequately fulfilled—even those that are not facing significant environmental pressures.

The essence of urban water security is an adequate response to (partly inevitable) system pressures. The response determines the degree to which pressures will alter the state and have an impact on system functions. Under an adequate response, system functions can be properly fulfilled even in high-pressure environments. However, cities facing pressures will never reach the same level of security as cities where these pressures are absent, because the risk that a pressure propagates along the cause-and-effect chain via an unexpected pathway is always present.

The urban water security dashboard provides a way to characterize different types of insecurity, recognizing the complicated causal processes that lead to a certain level of water security. We revealed hidden dimensions of water security and operationalized the concept of water security in a broad, yet practicable, way.

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Supplemental Data

The indicator formalizations and all dashboards and scores are available online in the ASCE Library (www.ascelibrary.org).

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