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Abstract

We review the increasing body of research on urban water security. First, we reflect on the four different focusses in water security literature: welfare, equity, sustainability and water-related risks. Second, we make an inventory of the multiple perspectives on urban water security: disciplinary perspectives (e.g. engineering, environmental, public policy, public health), problem-oriented perspectives (e.g. water shortage, flooding, water pollution), goal-oriented perspectives (e.g. better water supply and sanitation, better sewerage and wastewater treatment, safety from flooding, proper urban drainage), integrated-water versus water-integrated perspectives, and policy analytical versus governance perspectives. Third, we take a systems perspective on urban water security, taking the pressure-state-impact-response structure as an analytical framework and link that to the 'urban water transitions framework' as proposed by Brown *et al* (*Water. Sci. Technol.* **59** 2009). A systems approach can be helpful to comprehend the complexity of the urban system, including its relation with its (global) environment, and better understand the dynamics of urban water security. Finally, we reflect on work done in the area of urban water security indices.

1. Introduction

Researchers, policy makers and business leaders increasingly talk about water security. Apparently, there is something at stake. The concept of water security is used from the household to the global level. In this paper, we focus on water security at the urban level. But first something about the concept in general. The term water security is fashionable, fitting in the current time spirit with its focus on all sorts of security issues, so one may wonder whether it is old wine in a new bottle (Lautze and Manthrithilake 2012). Indeed, it seems that a lot of writings that previously went under headings such as integrated and sustainable water management now go under this new heading of water security. At the same time, however, the changing terminologies over time also reflect changing insights and changing focusses. Halfway through the 1980s, scholars increasingly spoke of *integrated* water (resources) management (figure 1), to highlight concerns that water problems could not be properly addressed if not taking a more holistic approach. It became clear that water systems had to be considered as a whole, since surface water and groundwater resources are linked, as are water quantity and water quality issues. Besides, it was acknowledged that water systems fulfil different functions, all to be considered in an integrated analysis. From around 1990 the term *sustainable* water (resources) management became rather popular as well, inspired by the successful uptake of the idea of sustainable development after the publication of the Brundtland report. A decade ago, the term *adaptive* water management became increasingly popular, inspired by the need to 'adapt' to climate change, but the term soon became used in a much broader way, referring to the need to continuously adapt to and flexibly respond to changing circumstances in general (Pahl-Wostl 2007). Other terms that have become increasingly popular recently are water risk, water resilience, water proof, and the water-food-energy nexus. Water security, however, is a term taking a central position. The term has got off the ground since around 2000, with the publication of *A Water Secure World* by the World Water Council (WWC 2000) and *Towards Water Security: A Framework for Action* by the Global Water Partnership (GWP 2000). Although

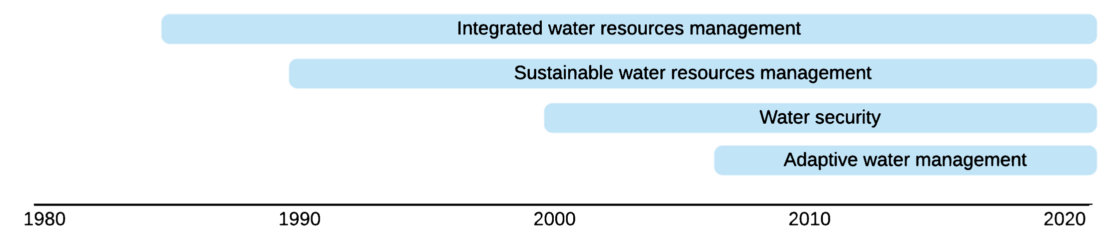

Figure 1. Emergence of new water management concepts over time.

the word *security* suggests a certain focus, in practice the term water security is generally taken so broad that it captures all that also goes under headings like integrated, sustainable and adaptive.

The concept of *urban* water security is different from the more general water security concept in its application to the territory of an urban area, a municipality or urban agglomeration. This introduces a number of elements that are specifically valid for urban water security, and not for water security at household, state, country or global level. The essence of an urban area is its high population density and dependence on its hinterland for the supply of its natural resources. For water this means that large urban areas are generally incapable of meeting their water supply from within the urban area itself. This is solved by supplying water resources from outside, sometimes from far away. McDonald *et al* (2014) call this the 'reach of urban water infrastructure'. Urban areas depend even more on water resources elsewhere for producing the food consumed by the urban citizens. This has been described as the 'external water footprint' of urban consumption (Hoekstra *et al* 2011, Hoff *et al* 2014). Since there are risks attached to such dependency, we speak here about the 'imported urban water risk'. This dependence on external water resources, through both water transfers for urban water supply and food imports for urban food supply, is an inherent and typical concern for water security at the urban level. In addition, the high density of people and economic activities in urban areas concentrates risks. This requires relatively high protection standards and sometimes different risk management approaches. Urban water security further differs from water security at other levels in the typical governance setting at this level, with different municipality departments responsible for distinctive water-related tasks or for tasks indirectly relevant (like spatial planning), with municipal policies but national regulations as well, with a public or private water supply utility and other policy processes and stakeholders typical to the urban level. Just like in the case of the water security concept in general, at the urban level there are various overlapping and competing terms used: integrated, sustainable and adaptive urban water management, urban water resilience, and water- and climate-proof cities.

The goal of this paper is to review the literature on urban water security. We have identified the most relevant scientific literature in Web of Science using the key words 'water security', 'urban water security', 'urban water management', 'urban water sustainability', 'urban water resilience', 'urban water vulnerability' and 'urban water risk', supplemented with an online search for urban water security and sustainability indicators and indices. In this review, we first reflect on the different interpretations of water security. Second, we make an inventory of the multiple perspectives on urban water security. Several authors have highlighted the multitude of relevant approaches before (e.g. Cook and Bakker 2012, van Beek and Linck-laen Arriens 2014), but by putting it all together we get a more comprehensive overview than in earlier contributions. Third, we take a systems perspective on urban water security, using the pressure-state-impact-response structure as an analytical framework, and link that to the 'urban water transitions framework' as proposed by Brown *et al* (2009). Finally, we reflect on work done in the area of urban water security indices.

2. What is water security?

The Global Water Partnership considers water security as the overarching goal of water management (GWP 2000). People, however, obviously differ in what they see as the goal. One may thus expect different definitions of water security. Besides, not everyone may agree on water security as the encompassing concept to reflect the overall goal of water management; some prefer to attach a narrower meaning to this concept and use it along with other concepts of equal or even greater importance. In the literature, we observe four different focusses when researchers define and study water security: it is about using water such that we are increasing economic *welfare*, enhancing social *equity*, moving towards long-term *sustainability* or reducing water-related *risks* (figure 2). Scholars often combine these points of view to different extents, but distinguishing the four interpretations helps to understand why treatments of urban water security often appear to be so different.

A focus on welfare seems all encompassing: the reason to care for an optimal water system and the best fulfilment of the various functions and services of the water system in an urban area is that this contributes to increasing urban welfare. Particularly when

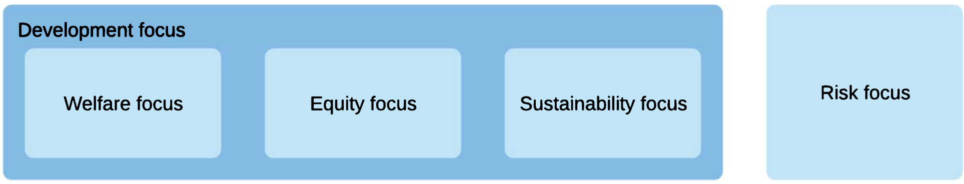

Figure 2. Different focusses in the definition and study of water security.

we interpret 'welfare' in broad terms, including ecological and social values and risks, the essence of water security boils down to increasing welfare for all in the long term. The value of different water system services (e.g. water supply, flood protection, green water corridors) could be measured in terms of their relative contribution to urban welfare. From this perspective, enhancing 'urban water security' more or less comes down to increasing the benefits from water in the city, as well as reducing or avoiding damage associated with water in the city. There is something to say for this, because welfare is an overall measure of development, but it can easily simplify the concept to an unacceptable level. Aesthetic, cultural and ecological values of water are difficult to capture in the (economic) terminology of welfare, and how benefits are distributed among citizens is generally not caught in an overall metric of welfare. This is not unimportant, because water insecurity often concerns particular groups, which may even be the essence of the whole concern about water security: that it does not reach all in society. It is the poor in a city that do not have access to proper drinking water supply and sanitation; the rich in the same city are perfectly fine. Another problem with measuring water security in terms of its contribution to welfare is the time dimension: water insecurity is not necessarily visible today, it may lie in processes that play out in the long term: continued urbanization in low-lying areas in the world, sea-level rise, land subsidence due to groundwater pumping, increasing frequency of extreme events like rains and river flows from upstream causing flooding, and increasing water demands while water availability is limited. The way welfare theoretic concepts deal with intergenerational transfers—the welfare of future generations—through discount rates is hotly debated (Goulder and Williams 2012). Finally, properly including risks in welfare metrics is known to be difficult, particularly given the fact that risks often include large uncertainties that are difficult to quantify but form part of the essence of water insecurity.

When the welfare focus is expanded to include equity and sustainability as well, van Beek and Lincklaen Arriens (2014) call this the 'development focus' on water security, which in their view then contrasts with the risk focus on water security. In the broader developmental approach, water security is something to improve over time, with certain goals and targets and a combination of policies, reforms, and investment projects to achieve those goals. This approach captures three of the four focusses mentioned: growth in welfare, equity and sustainability. The risk-based approach centres around the fourth focus: managing risks and reducing vulnerability to shocks from climate variability and water-related disasters. Van Beek and Lincklaen Arriens (2014) argue that these two approaches are complementary, and need to be pursued simultaneously and in a balanced manner. Many scholars, however, interpret water security narrower. Among those scholars that take a developmental approach to water security we see that some focus more on economic growth (Sadoff *et al* 2015), while others focus on the equitable distribution of water values across individuals (Zeitoun 2011) and yet others on the sustainability of water management (Bogardi *et al* 2012). Grey *et al* (2013) take the exclusive risk standpoint by defining water security as a tolerable level of water-related risk to society. According to Hall and Borgomeo (2013), this focus on water risks is congruent with the language of 'security' and brings theoretic, empirical and operational substance to the term 'water security'. They argue that the risk approach allows the estimation of the effectiveness of investment of resources in reducing water-related risks in terms of their marginal benefit. The downside of this approach, which is grounded primarily in engineering and economic traditions, is that it tends to oversimplify by representing uncertainties through calculable risks and thus underplay diversity and politics in society (Zeitoun *et al* 2016). The risk approach easily comes down to a cost-benefit analysis at macro-economic level with a main focus on overall welfare, with an undervaluation of issues of equity and sustainability, values that are difficult to quantify, and uncertainties. A more holistic approach to water security is taken by GWP (2012), which describes a water secure world as one in which 'there is enough water for social and economic development and for ecosystems. It integrates a concern for the intrinsic value of water together with its full range of uses for human survival and well-being. It harnesses water's productive power and minimises its destructive force. It is a world where every person has enough safe, affordable water to lead a clean, healthy and productive life. It is a world where communities are protected from floods, droughts, landslides, erosion and water-borne diseases.' According to GWP (2012), water security further means 'addressing environmental protection and the negative effects of poor

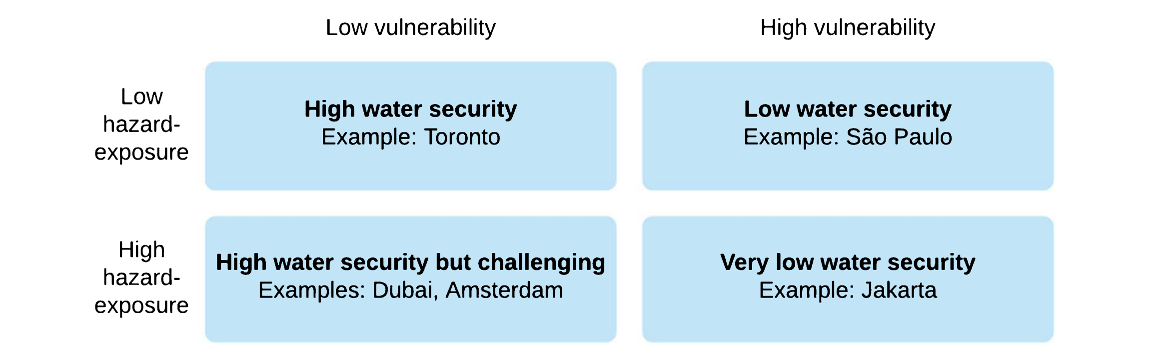

Figure 3. Hazard-exposure versus vulnerability.

management, which will become more challenging as climatic variability increases. A water secure world reduces poverty, advances education, and increases living standards. It is a world where there is an improved quality of life for all, especially for the most vulnerable—usually women and children—who benefit most from good water governance.' Such a lengthy description of what water security encompasses definitely increases the chance that nothing important is left out, but at the same time of course it excludes clarity about trade-offs that will need to be made. In this sense, it is rather a concept that brings people together to start a discussion about important issues around water than a well-defined measurable concept.

Regarding water security from a risk viewpoint, a few additional remarks are to be made. Risk is a combination of hazard, exposure and vulnerability (Garrick and Hall 2014). Possible hazards include, for example, drought, flooding, and water quality deterioration. Exposure is always relatively high in urban areas due to the concentration of people and assets. A city may be vulnerable because of ill-preparedness, while another city facing the same hazards may be much less vulnerable because of proper adaptation, sufficient coping capacity and measures to increase resilience. Cities facing relatively low water hazard-exposure, may still have high vulnerability due to, for instance, poor water infrastructure. Two cities may have a similar overall 'risk' or 'security' but differ in terms of the underlying factors: low hazard-exposure may come with high vulnerability (e.g. bad infrastructure, bad governance), while high hazard-exposure may come with low vulnerability (well-preparedness). These situations may result in similar 'overall' risk or security levels, but they are fundamentally different. In the one case, the natural conditions may be quite good while risks increase due to inappropriate management, leading for example to water pollution and sub-optimal water supply. In the other case, the natural conditions may pose all sorts of challenges, like water shortages and floods, while proper management reduces risk. For this reason, it will always be essential to explicitly distinguish between hazard-exposure and vulnerability underlying a certain overall risk level (figure 3). An example of relatively low hazard-exposure combined with low vulnerability is Toronto, a city with a moderate continental climate with monthly rainfall constant over the year. Lake Ontario provides a very large freshwater buffer, although it also gives some storm surge hazard. The combination of high hazard-exposure and low vulnerability is probably valid for Dubai, which has a hot desert climate, very little rainfall and hardly any freshwater resources. However, the big wealth of the city enables the government to fulfil the enormous freshwater demand by energy consuming desalination technologies. Less preparedness exists though for incidental rain showers. Another, but very different example of high hazard-exposure but low vulnerability is Amsterdam, which faces a substantial flood hazard, resulting from its elevation at around sea level in combination with the occurrence of large storm surges at the North Sea. However, the very high standard of flood protection infrastructure provides that flooding has not occurred in recent history. The opposite of low hazard-exposure but high vulnerability is found in São Paulo, which, with 1400 mm y^{-1}, receives a large amount of rainfall annually. The water demand in this metropolis is very high, but the surrounding basins theoretically offer sufficient water to supply the city; poor infrastructure and management, however, results in regular water shortages, and water pollution in the city is considerable as well. Finally, the combination of high hazard-exposure and high vulnerability can be found in Jakarta. Located in a low-lying, subsiding delta and challenged by heavy monsoon rains, the city is threatened by a substantial flood risk. The city is very large, not wealthy and has a lot of slums. Although the area is water-abundant, the groundwater resources are heavily overexploited and the quality of freshwater resources is severely deteriorated. Riverine and storm water flooding is occurring on a yearly basis.

3. Multiple perspectives on urban water security

3.1. Disciplinary perspectives

Scientists from different disciplinary backgrounds appear to give different interpretations to the term water security. Cook and Bakker (2012) discuss

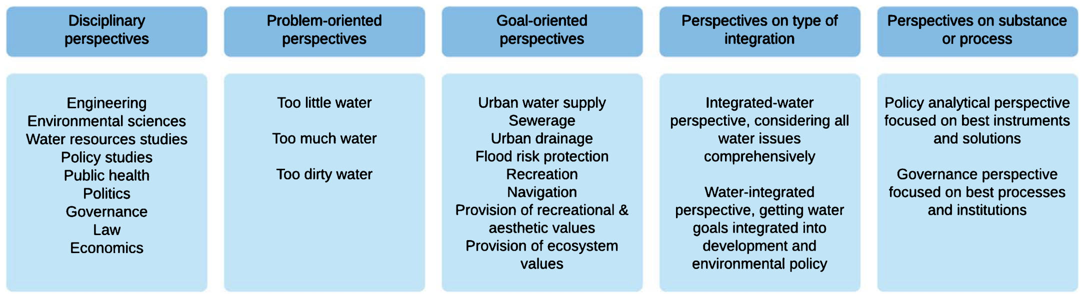

Figure 4. Multiple perspectives on urban water security.

framings of water security across the physical and social sciences. They find that in the engineering domain, water security studies generally focus on protection against water related hazards (floods, droughts, contamination, and terrorism) and water supply security (percentage of demand satisfied). Water resources studies rather focus on water scarcity, and water supply and demand management. Environmental studies generally focus on the access to water functions and services for humans and the environment, on water availability in terms of quality and quantity, and on minimizing impacts of hydrological variability. Policy studies focus on interdisciplinary linkages (food, climate, energy, economy and human security), protection against water-related hazards, and sustainable development of water resources to ensure access to water functions and services. Public health studies put emphasis on supply security and access to safe water, and prevention and assessment of contamination of water in distribution systems. We can add to this the political perspective focusing on power structures, equity issues and conflicts over water, the governance perspective focusing on planning, institutional arrangements and division of responsibilities, the legal perspective focusing on water rights and ownership, and the economic perspective focussing on the efficiency of water resources use, the economics of water demand and supply, water pricing and market mechanisms, cost-benefit analysis of flood risk protection and water quality conservation, valuation of environmental services of water systems, and internalization of externalities (figure 4). Cook and Bakker (2012) observe that different disciplines also tend to analyse at different scales: whereas development studies often consider the national scale, hydrologic studies generally employ a catchment scale, and social scientific studies usually focus on the community scale. Recognizing the multiple disciplinary perspectives and multiple spatial scales involved, the 2013 Bonn Declaration on Global Water Security (GWSP 2013) calls for a renewed commitment to adopt a multi-scale and interdisciplinary approach to water science. Interestingly though, the declaration is highly water-centric, calling to address water challenges through a broad water agenda and innovation in water institutions. A true interdisciplinary approach should allow for a much wider array of perspectives, recognizing that water security is intricately linked to human development, governance in broader sense than 'water governance', food and energy security, social equity, and environmental sustainability.

3.2. Problem-oriented perspectives

Urban water issues can be summarised as 'too little, too much, too dirty'. Underneath this simplification lies a myriad of complex and interrelated problems and challenges. Urban areas have very high levels of human interference in natural hydrological processes (Niemczynowicz 1999) to support water supply and sanitation, storm-water management, and flood protection. Water scarcity–too little—can be natural, for instance due to droughts or in desert cities, but can also be the result of over-use and poor management (Rijsberman 2005, Padowski *et al* 2016). Water scarcity can be addressed with infrastructure, yet dams, canals, desalination plants and other technical solutions are not without problems: they usually require considerable funding; municipalities need to collaborate with regional and national administrations to access water resources that are outside their jurisdiction; and large-scale infrastructure development can have significant environmental and social impacts. Water demand management as a way to address scarcity receives increasing attention, yet changing peoples' behaviour to curb wastage and achieve efficient allocation of water to its most valuable use is fraught with behavioural, social, economic and political challenges (Fielding *et al* 2013). Flooding—too much water—can originate from the sea (coastal floods), rivers (fluvial floods) and rain (pluvial floods). These causes are often linked: heavy rains causing swollen rivers with backflow due to high tides driven by storms. Cities in river deltas are especially vulnerable to flooding. Still, people tend to settle in flood prone areas because of the fertility of land and accessibility of water transport, resulting in complex interactions and feedbacks between sociological and hydrological processes (Di Baldassarre *et al* 2013). Water pollution—too dirty—can contribute to water scarcity and impact health of ecosystems and humans (Biswas and Tortajada 2011). When groundwater or surface water resources are contaminated they are not suitable for supplying drinking water without treatment, while poor citizens may not be able to afford treatment and are subject to health risks. Infectious and non-infectious waterborne diseases are globally a major source of human suffering and economic damage. Poor sanitation can cause urban water pollution, while a range of other point and diffuse sources of urban water pollution exist as well, including industrial discharge and surface runoff. In many ways, addressing water quality issues is much more complex than addressing water quantity issues (Biswas and Tortajada 2011, Falkenmark 2011).

Urban water systems interact with many other systems and hence are affected in indirect ways, and at the same time water problems indirectly cause other issues. In this respect, Zeitoun (2011) introduces a 'web' of water security that focuses on interdependencies of physical and social processes and interdependencies with other security areas, such as climate security, food security, energy security and human security. A clear example of complex interactions at the urban scale is the issue of land subsidence. Over-abstraction of groundwater in many coastal cities, most notably Jakarta (Abidin *et al* 2011), causes subsidence resulting in increasing coastal, fluvial and pluvial flood hazards, and water quality is affected through saline intrusion. Lack of good quality surface water, inadequate investments in and governance of water supply, and poor enforcement of groundwater pumping contribute to worsening urban water security. Another example of interdependencies is the phasing out of a relatively large and viable pig farming industry in the 1980s in Singapore due to water quality concerns (Tortajada *et al* 2013), while at the same time industrial policies have increased the share of non-domestic water consumption to 55% in the city-state (www.pub.gov.sg), showing the strong interaction of water, social and economic issues. Interaction of urban water systems with other systems also takes place at the regional, national and global scale through the water footprint of urban consumers (Paterson *et al* 2015). Consumption of food and other commodities in cities affects water use elsewhere, while at the same time dependence on water resources elsewhere through trade can affect urban water security.

Urban water issues are dynamic. A range of socio-economic, environmental and governance-related drivers cause adaptations and transformations in urban water systems over time (Daniell *et al* 2015). Changing patterns of temperature, evaporation and precipitation as a result of climate change, growing urban populations, changing river flows as a result of upstream water and land use changes, technological changes and development of new preferences and norms are all examples of drivers for changes in the way water is being managed. The dynamics occur across different scales (Wheater and Gober 2013). Water issues at the urban scale are connected to global climate change, regional basin changes and changes in consumption preferences of citizens. The dynamics and cross-scale interlinked systems give rise to complexity and uncertainty challenges that need to be addressed to improve urban water security.

3.3. Goal-oriented perspectives

Water security is often conceived as a good or as a goal to be achieved. The traditional water management literature speaks about the 'functions of a water system'. In the environmental sciences, a more common term is 'ecosystem services' or 'environmental services', which when applied to water systems translates into 'water system services'. Typical water-related services to be fulfilled include: urban water supply; sewerage; urban drainage; flood risk protection; navigation; provision of recreational and aesthetic values; and provision of ecosystem values. Much of the urban water security literature considers various aspects of the different water systems functions. According to Larsen *et al* (2016), the top priorities for urban water sustainability include the provision of safe drinking water, wastewater handling for public health, and protection against flooding. But often 'water security' is narrowed down to just 'water supply security' (e.g. Lundqvist *et al* 2003, Padowski *et al* 2016, Grafton 2017). An important driver of the focus on water supply has been the UN goal to increase the number of people with adequate water supply and sanitation, as first laid down in the Millennium Development Goals and later in the Sustainable Development Goals. The goal-oriented perspective raises the question of water security for whom: for every urban citizen equally, or primarily for the richer areas and business districts of the city; and for the water users in the city, or also for those users in the catchments where water is extracted for urban use. The question 'security for whom' often remains unanswered.

3.4. Integrated-water versus water-integrated perspectives

Whereas many studies are rooted in the idea of integrated water management, acknowledging that one should consider all aspects of water in coherence, water is increasingly seen as just one component that should be integrated in the broader scope of development and environmental policy. For instance, water security is increasingly being studied in relation to food and energy security. Most of those studies do not particularly relate to the urban level, but several do. Most of the urban water footprint studies show that the external water dependency particularly relates to food import into the city. Urban food essentially depends on the availability of sufficient land and water resources elsewhere to produce the food. In some cases, urban energy security also depends on the water resources elsewhere, for instance in the case of urban electricity depending on hydropower. But also in the case of electricity through thermoelectric power plants, water scarcity can affect energy supply,

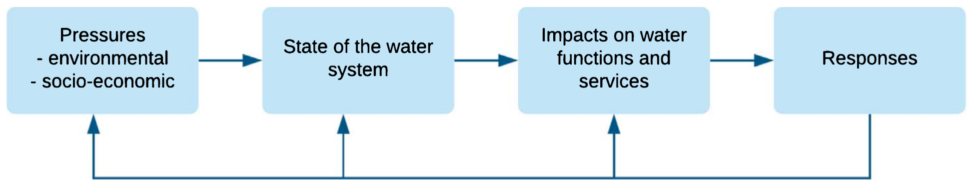

Figure 5. Pressure-state-impact-response schematization.

as Sovacool and Sovacool (2009) show for four metropolitan areas in the US (Houston, Atlanta, Las Vegas, New York). With ongoing replacement of fossil fuels by biofuels, urban transport increasingly relies on external land and water resources elsewhere again to grow the biomass required to produce the biofuels. Conversely, urban water supply is consuming increasing amounts of energy (Kenway *et al* 2011). It has been estimated that the California State Water Project, delivering water mostly to urban water users in California, is the largest single user of energy in California, using 2–3% of all electricity consumed in the state, which is equivalent to about one-third of the total average household electric use in the region (Cohen *et al* 2004). Urban water management measures (like water conservation or reuse) may actually greatly impact on energy use and carbon emissions as Shrestha *et al* (2012) show in a case study for Las Vegas. The concept of 'integrated water management' may thus be replaced by an increasing need to get water concerns integrated into urban planning and urban energy and food supply policies.

3.5. Policy analytical versus governance perspectives

Water security is not just about having a good water system status and about the proper fulfilment of various water system functions, but it is also about good governance (Bakker and Morinville 2013). Urban water security requires both integrated analysis and planning (considering all aspects and functions of the water system) and coherent policy making across different relevant governmental institutions. In practice, though, we observe that scholarly emphasis generally lies on the one or the other. Whereas engineers and urban planners tend to design effective solutions on the drawing table, underestimating the processes needed to actually implement those solutions, public administration and political scientists are inclined to worry about policy processes, stakeholder interactions, legitimacy and power, looking for mechanisms of good governance but underestimating the quality and effectiveness of policy outcomes. 'Good' solutions on the drawing table are often not feasible (hence one may question whether they are good), but 'good' governance does not guarantee outcomes that are effective in terms of solving the problems at hand. The final result depends on balanced attention to both the bureaucratic and technocratic aspects of planning and the administrative, institutional and political aspects of governance. There is rather good knowledge, for example, what could be efficient and effective water pricing schemes, but the likelihood that changes in water pricing structures are accepted at all may be rather a function of smart governance, finding the right coalitions, making combinations with other issues, and balancing interests.

4. A systems perspective on urban water security

For an understanding of the complexity and time dimension of urban water security, it can be helpful to adopt a system-dynamic perspective, acknowledging that many variables, causal mechanisms and feedback processes play a role. In other fields of environmental study, the pressure-state-impact-response schematization of social-environmental systems facing change has been proven helpful in one form or another in a first rough description of what makes systems change (e.g. OECD 1993, EEA 1999, Hoekstra 2000). First of all, there are the driving mechanisms of change that exert pressure on the system (figure 5). In the case of urban areas, major pressures that change the water system include both environmental pressures (like land use and cover changes and climatic changes within the urban area, and changes external to the urban area, like changing water availability in the areas on which urban consumption depends and sea level rise) and socio-economic pressures (like continued population growth, changing water demands). The state of the water system can be described in terms of water stocks and flows within the area, exchanges with its surrounding areas, occurrence of extreme events such as droughts and flooding, water quality and available infrastructure. Impacts of the water system state on its functions or services can be described in terms of actual (clean) water supplied and security of (clean) water supply, actual flood protection levels provided, etc. Finally, responses can include institutional reform, new plans, implementation of plans and operation and maintenance. Effective responses will reduce pressures (e.g. moderate continued urbanization, decrease water demand through water pricing or other measures), improve the state of the system (e.g. through improved infrastructure) or reduce impacts (e.g. through spatial zoning, disaster planning). In the complex, dynamic systems that cities are, where social and physical processes interact, understanding of feedback loops is important, as they can cause lock-ins, such as the levee effect described below, and undesirable outcomes of responses. Urban water security is equally complex and dynamic: transitions over time affect the water security of a city and require anticipatory and proactive responses.

4.1. Pressures

Cities face a large number of pressures that affect water security. The pressures can be grouped in socio-economic and environmental factors. An important socio-economic factor is urbanization: in growing cities water demands increase with population growth and on top of that per capita consumption increases with economic development. To meet increasing demands, renewable local water resources may not be sufficient, leading to over-exploitation of surface water and groundwater resources, including the consumption of fossil groundwater, or the need to use (additional) external water resources. Most cities already depend on water resources from outside the municipal boundaries (McDonald *et al* 2014) and growth means that increasingly remote water resources need to be tapped, either from within the same catchment where the city lies or from other catchments, possibly conflicting with other water uses. The water footprint of growing cities also expands, and cities with large external water footprints could face pressures from unsustainable production in source regions. With more people and assets, exposure to water-related hazards also increases. Flooding risks can increase as impervious areas expand, and more people generate more waste affecting water quality. In developing cities existence of slums and families living below the poverty line may add to the pressures as these areas have no proper water and sanitation infrastructure. In addition, some cities can face specific socio-economic pressures, such as the presence of water-intensive industries, widespread open defecation or gender issues in access to water and sanitation.

Environmental pressures are caused by the hydrological and geographical conditions in the area where a city is located and changes in these conditions. Some cities are located in areas with an unfavourable climate, such as an arid climate, a climate with large intra or inter-annual variability in precipitation, or in areas prone to hazards such as hurricanes, floods and droughts. Climate change modifies these conditions in the long run, changing the water security situation as well. Cities may be located in low-lying areas and threatened by sea level rise and land subsidence. Land subsidence is often the result of urbanization when unsustainable groundwater abstraction takes place to meet increasing demand, as mentioned before, or by drainage to make wetlands suitable for urban expansion.

Further growth of cities and climate change are likely to cause larger water stress in cities, both in terms of flood problems and water scarcity, while higher temperatures could also affect water quality. McDonald *et al* (2011) estimate the amount of water physically available near cities and show that currently 150 million people live in cities with perennial water shortage, defined as having less than 100 litre per person per day of sustainable surface and groundwater flow within their urban extent. They further estimate that by 2050, demographic growth will increase this figure to almost 1 billion people. Climate change will cause water shortage for an additional 100 million urbanites. Freshwater ecosystems in river basins with large populations of urbanites with insufficient water will likely experience flow regimes that do not longer meet the environmental flow requirements to maintain.

4.2. State of the water system

The state of an urban water system concerns the quantity and quality of water, and the infrastructure to manage these. The quantity of water in a city can be described in terms of water stocks and flows and exchanges with areas outside the municipal boundaries. Groundwater extraction from wells within and outside municipal boundaries is an important source for urban water supply. For instance, a study conducted in 1998 found that in northern China half of the urban water demand was met by groundwater, with a rapid decline of water levels in most cities since the late 1970s (Zaisheng 1998). Globally, many aquifers are overexploited: water withdrawals are exceeding aquifer recharge leading to depletion of the aquifer (Wada *et al* 2010). Surface water is another important source for urban water supply. Many cities are located on river banks, yet water abstraction points are often located upstream where water quality is better, as in the city and downstream sewage water is discharged. Reservoirs can be constructed to create a buffer to manage variability in surface flows. To assess the state of river flows they can be compared to what they would be under undisturbed conditions and to environmental flow standards (e.g. minimum flows to maintain certain ecosystem values). Similarly, surface water and groundwater quality can be compared to ambient water quality standards, for both chemical and biological pollutants. Biological contamination is particularly relevant for shallow groundwater wells, often used by households in cities with inadequate water supply systems, which are contaminated from leaking sanitation infrastructure (leaking sewers, septic tanks, latrines, etc.). Aside from groundwater contamination, pollutants can accumulate in surface water sediments over time. In coastal cities, salt water intrusion can also affect the state of the water system and make groundwater wells unusable. Finally, it should also be noted that there is a strong link between solid waste management in a city and garbage in streams and canals.

Water supply infrastructure, sanitation infrastructure and flood protection infrastructure should be considered when looking at the state of urban water infrastructure. Relevant indicators for the state of the infrastructure include coverage of water supply systems in terms of connection rates and supply capacity; drinking water quality standards; percentages of wastewater collection and treatment, distinguishing between primary, secondary and tertiary treatment; leakages in drinking water supply and sewerage systems; and adequacy of stormwater and flood protection infrastructure (levees, weirs). The latter should be benchmarked against projections for sea level rise and climate change as the investment horizon for this type of infrastructure is long.

4.3. Impacts on water services and functions

While the state of the water system is mostly described in physical terms, the impacts focus on how well the water system provides its water supply and sanitation, flood protection, recreational, environmental and other services. A wide variety of indicators is used to benchmark water utilities (Berg and Marques 2011, www.ib-net.org); in addition to indicators for the performance of the physical infrastructure, these also include for instance management and financial performance indicators. For water supply, the ultimate impact following pressures and state is how many people have adequate water supply and sanitation services: the infrastructure may be there, e.g. households may have a connection to the water supply system, but if water supply does not meet demand, breaks down during droughts, or is contaminated, impacts on households' wellbeing may be severe. Similarly, if water can be supplied, but it is not affordable for poor households, the water system is not functioning properly. Occurrence of waterborne diseases is a measurable impact of inadequate water supply and sanitation. Similarly, coastal, river and stormwater flood protection infrastructure may be present, but ultimately what counts is that floods do not occur. Frequency, severity and extent of flooding are important physical indicators for adequacy of flood protection infrastructure, while annual damages and casualties focus on the social dimension. Human use of water resources in cities has severe impact on the environmental services: biodiversity decreases as compared to reference situations or targets, toxics and plastics can end up in aquatic species, algae bloom frequencies can increase and fish kill incidents can occur. Finally, water has an aesthetic and recreational function in many cities such as Venice, Amsterdam, Stockholm and Singapore. The degree of cleanliness of waterways and waterbodies directly impacts these functions (Carson and Mitchell 1993).

Urban water impacts extend beyond the municipal boundaries. As cities depend on external water resources, conflicts over limited supplies could arise. Rural water uses are usually sacrificed for urban uses, but rural users would need to be adequately compensated for any negative impacts, such as loss of income. In addition there is the dependence of the water footprint of urban consumers on external water resources for producing the food consumed within the city. For both types of dependence, the impact is not so much related to the dependence itself, this is inherent to urban areas, but the degree to which the dependency on external water resources is unsustainable given the available water resources in the source regions.

4.4. Response

Response aims to decrease pressures, improve the functioning of the water system and reduce negative impacts of a malfunctioning water system on water services and functions (Sekovski *et al* 2012). Response results from a perceived mismatch between an actual and desired situation or from a undesirable future situation. While the focus is usually on governmental response, societal response is equally important. An example of the latter is the installation of household groundwater wells in cities with an inadequate piped water supply system. As urban water systems are complex and dynamic, responses require innovation and development in almost all technical, institutional and organizational dimensions (Larsen *et al* 2016) with their own timeframes and scopes. In addition, many responses require dealing with uncertainty and ambiguity, e.g. when it concerns policy-making for future climate change. Consequently, a significant body of literature exists on policy or decision-making under uncertainty and creating resilient, adaptive and robust systems in the (urban) water sector (e.g. Gersonius *et al* 2016, Johannessen and Wamsler 2017). Larsen *et al* (2016) discuss five alternative non-exclusive and partly overlapping solutions to conventional urban water management (table 1). Although there are many more, city and case-specific responses, these five responses cover a good part of the challenges cities globally face.

4.5. Transitions over time

Based on a historical analysis of the changing institutional and technological arrangements supporting Australia's urban water management practices over the last 200 years, Brown *et al* (2009) propose a framework to understand how urban water management in cities generally transitions when moving towards sustainable urban water conditions. They distinguish between six subsequent stages in the 'urban water management transitions framework' (figure 6): the water supply city (with a focus on the effective provision of safe and secure water supply), the sewered city (added focus on sewerage in response to epidemic outbreak of diseases), the drained city (added focus on urban drainage in response to the increasing damage from stormwater), the waterways city (added focus on the cleanliness of water bodies and wastewater treatment in response to increasing water pollution), the water cycle city (added focus on water demand management and closing water and substance cycles in response to limitations to water supply and assimilation of pollution), and the water sensitive city (added focus on

Table 1. Emerging solutions to urban water challenges (after Larsen *et al* 2016).

Local water storage and stormwater drainage	Concepts such as low impact development, water sensitive urban design and sustainable urban drainage systems try to address the negative impacts of urbanization on stormwater runoff (Fletcher *et al* 2015), and in some cases also to sustainably increase the use of urban catchment water as a resource. Green roofs, rainwater harvesting and local water storage may flatten runoff peaks and increase local water supply.
Increasing water productivity and non-conventional water sources	Water recycling and reuse aim to increase water productivity. Several cities in water-stressed areas treat wastewater for use in irrigation or other uses. A few cities, e.g. Singapore and Windhoek, have developed systems to recycle wastewater for potable use (van Rensburg 2016), although direct potable use still faces emotional and psychological barriers (Leong 2016). Desalination is another technology to increase supply, but it is still more energy-intensive than water recycling.
Waste prevention and separation of waste at the source	Reducing the use of potentially harmful chemicals and preventing them from ending up in wastewater can reduce water pollution and the challenge of wastewater treatment significantly. Water recycling can be supported by source separation of wastewater, which makes recovering nutrients and energy easier.
Distributed or on-site treatments	With advancing technology, the need for large centralized infrastructure could reduce in favour of distributed, on-site systems that can be implemented in the short-term and can be suitable especially for cities that currently have poor infrastructure as they do not require large-scale investments.
Institutional and organizational reforms	Many undesirable pressures, states and impacts are the result of governance failures at multiple levels of governance (Pahl-Wostl 2017) and require institutional and organizational reforms. Involvement of the private sector and decentralization have been proposed as panaceas, yet water policy and management is complex and new perspectives, concepts and frameworks, such as adaptive and transformative change, social learning, self-organizing systems, informal networks and poli-centricity have emerged to understand this.

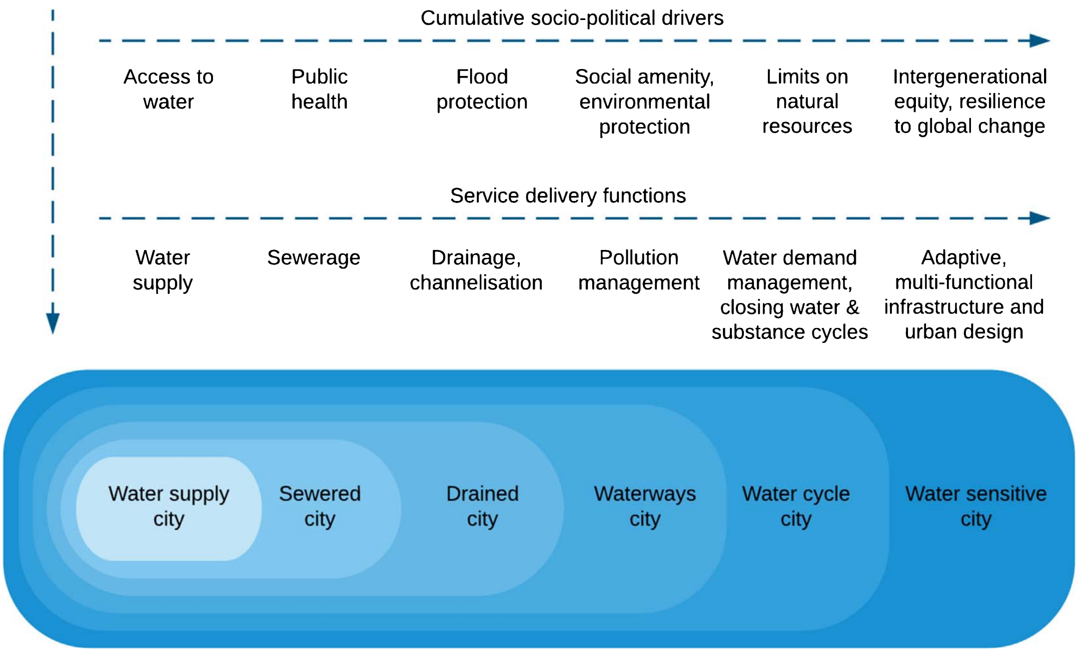

Figure 6. Urban water management transitions framework (based on Brown *et al* 2009).

adaptive, multi-functional infrastructure and urban design reinforcing water-sensitive behaviours as a response to climate change). The transitions are underpinned by cumulative socio-political drives and in each stage new service delivery functions are added. There are currently no 'water sensitive cities' in the world, but according to Brown *et al* (2009) the concept is attracting increasing attention from scientists and practitioners. The transitions framework suggests that each stage brings urban water management at a higher level of advancement, and one may argue a higher level of 'water security'. Yet, as acknowledged by Brown *et al* (2009), the transitions through different stages is not so linear. Different aspects of urban water systems can be at different stages concurrently and besides progression, also degradation is possible. These complex dynamics cause water security to change over time, and sometimes not in obvious ways. An example is the levee effect (Di Baldassarre *et al* 2013), whereby levees to protect against floods meant to increase water security actually increase the vulnerability, and hence reduce water security, as people have no longer experience to deal with floods and protected areas develop faster.

Table 2. Overview of urban water and sustainability indices.

Urban water indices		Urban sustainability indices	
City Blueprint	van Leeuwen *et al* (2012), Koop and van Leeuwen (2015)	Green City Index	Siemens (2012)
Sustainable City Water Index	Arcadis (2016)	City Resilience Index	Arup (2014)
Water Provision Resilience Index	Milman and Short (2008)	SDEWES Index	SDEWES Centre (2017)
Sustainability Index for Integrated Urban Water Management	Carden and Armitage (2013)	National Water Security Index, including the aspect of urban water security	ADB (2013, 2016)
Urban Water Security Indices and Indicators	Jensen and Wu (2018)		

5. Urban water security indices

As discussed in this paper, urban water security is a very broad concept that can be approached from many different perspectives. The concept is often used qualitatively, yet there is value and interest in quantitatively measuring urban water security (van Beek and Lincklaen Arriens 2014). Quantification of urban water security makes the concept more concrete and can help to carry out assessments, prioritise actions and investments, track progress and inform decisions (Dickson *et al* 2016). Indicators and indices can be a powerful communication tool to facilitate discussions between different stakeholders. There is a very large number of water (security) indicators and indices (Plummer *et al* 2012, Dickson *et al* 2016), though only a few focus specifically on urban water security (table 2).

The City Blueprint (van Leeuwen *et al* 2012) is a dedicated framework for the assessment of the sustainability of urban water management. The updated version (Koop and van Leeuwen 2015) focuses on indicators that are within control of local water authorities, and hence it excludes trends and pressures, such as climatological variables, water imports and exports (dependent on socio-economic processes), and surface water quality (assumed to be caused by upstream pollution; wastewater treatment is used as an indicator for surface water quality). Hence, the index can be considered rather as an assessment of integrated urban water resources management performance than a comprehensive water security index. Data for the City Blueprint is collected from public sources and assessments by experts and local water authorities. In general, the framework heavily relies on the data that is available for European cities and for several indicators country-level data is used rather than city-level data. The Sustainable City Water Index was developed as 'a tool to help inform future improvement and long-term water sustainability' (Arcadis 2016). It is a normalised index ranking cities relative to each other. The index distinguishes three main categories: resiliency, efficiency and quality, with data obtained from global datasets of variable spatial levels and municipal water utilities. The European cities score high, with a top-5 consisting of Rotterdam, Copenhagen, Amsterdam, Berlin and Brussels. This may be due to a focus on responses; for instance, Rotterdam still receives an average score for flooding even though it is a coastal city below sea level because good flood protection measures are in place. Urban water security also has a time dimension. Milman and Short (2008) argue that this dimension is often overlooked by existing sustainability indicators. They propose a Water Provision Resilience Index that incorporates the notion of resilience to reflect changes in the state of the water system over time. The index measures how well an urban water provider is able to maintain or improve the percentage of the population with access to safe water into the future. A qualitative questionnaire is used to assess performance in six critical aspects of urban water supply systems: supply, infrastructure, service provision, finances, water quality and governance. The Sustainability Index for Integrated Urban Water Management (Carden and Armitage 2013) is a composite index comprising four categories (social, economic, environmental and institutional), which are represented by a total of 16 indicators that are calculated using a total of 35 variables. Using standardisation and means a score for each category is determined. The index was applied to ten cities in South Africa. Jensen and Wu (2018) develop a new urban water security index based on indicators in four categories: water resource availability, access to water, water-related risks, and institutional capacity to manage water resources. They apply this framework to two pilot cities.

In addition to these urban water security indicators there are urban sustainability and resilience indicators that include water issues, such as the Green City Index (Siemens 2012) which includes one category of water indicators, the City Resilience Index (Arup 2014) with 52 indicators of which several link to water, and the SDEWES Index (SDEWES Centre 2017), which includes a category for water and environmental quality. Furthermore, there are several composite water security indices developed for basin or country comparisons (e.g. Lautze and Manthrithilake 2012, ADB 2013, Animesh *et al* 2016, Vörösmarty *et al* 2010, Gassert *et al* 2014). The National Water Security Index from ADB (2013, 2016) includes five aspects, of which one is urban water security. Urban water security is measured through indicators of water supply, wastewater treatment, and drainage (flood damage), with factors added for urbanisation rate and river health. ADB (2016) suggests a correlation between national water security and GDP and between national water security and quality of governance as well.

Although integrated, comprehensive indices of water security can be useful for many purposes, they suffer from conceptual and methodological issues (Garrick and Hall 2014, Molle and Mollinga 2003). Water systems are complex with many interacting parts and causality is often not clear. All indices discussed above have issues with data availability, requiring the research to make assumptions, use expert opinion or use proxy data, e.g. country level data for cities, even though geographical variation may be large. Data quality may also be an issue and needs to be discussed clearly to avoid wrong interpretations. Composite indices usually classify indicators into several categories or tiers, with results displayed at a higher tier. Constructing indices and indicators that combine several dimensions requires subjectively assigning weights (including equal weights) and results in information loss. A dashboard approach, in which all individual variables are displayed, may partly remedy this.

6. Conclusion

In its most comprehensive interpretation, the concept of urban water security addresses the fulfilment of all different 'water system services', considers overall welfare as well as social equity and environmental sustainability, and addresses both risks and uncertainties. Risks include hazards, exposure and vulnerability, the latter including aspects of coping capability and resilience. In this all-encompassing approach, urban water security may be seen more or less as equal to what others would call 'urban water sustainability' (when interpreted in its broadest sense as well). Therefore, it can happen that what the one calls a 'sustainable cities water index' may actually aim to capture the same as what others would call an urban water security index. A systems approach can be helpful to comprehend the complexity of the urban system, including its relation with its (global) environment, and better understand the dynamics of urban water security.

Future research may focus on the question how to transition towards cities that are more inherently healthy, sustainable and resilient. Most cities in the world are still struggling to solve problems created (water shortages, water pollution, flood vulnerability), using end-of-pipe solutions (larger pipes carrying in water from further away, wastewater treatment, dikes). We need to better understand the full potential of water sensitive design, rainwater harvesting, recycling, reuse, pollution prevention and other innovative urban water approaches. We need to consider 'integrated water' approaches, where all water issues are considered comprehensively and in their mutual interdependencies, as well as 'water integrated' approaches, whereby handling water wisely forms an integral part of urban dynamics and urban design. Understanding and finding suitable governance arrangements in local contexts supporting these approaches is a clear research need as well. In addition, a proper understanding of the fundamental dependence of urban areas on their local hinterland for water supply and the global hinterland for supply of food and other water-intensive goods, will be needed to understand the true water security of cities in the long run.

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