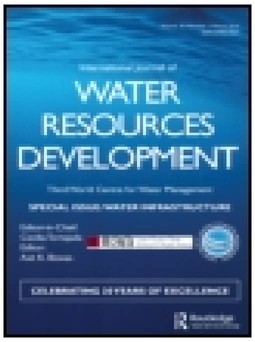

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Strategies for urban drought risk management: a comparison of 10 large cities

Joost Buurman[a], Marjolein J. P. Mens[b] and Ruben J. Dahm[b]

[a]Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore; [b]Deltares, Delft, the Netherlands

ABSTRACT
Sustainable development of cities requires robust water supply systems, yet many cities need to resort to ad hoc measures when faced with a drought. This article aims to explore how cities can do better in reducing the risk of water shortage due to drought. To that end, a classification of drought measures in urban water supply systems is proposed, and then applied to 10 cities that recently faced a drought. We find that these cities used a relatively limited number and variety of measures. The classification can help cities evaluate different types of measures for reducing long-term water stress and limit the impact of extreme droughts.

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Introduction

Droughts affect freshwater resources, and cities may experience water shortages. Water rationing and supply disruptions can cripple production processes, and communities may incur high costs searching for alternative sources of water. The sustainable growth of cities depends on reliable water supply systems that are robust enough to cope with droughts. The Intergovernmental Panel on Climate Change (IPCC, 2014) has concluded with medium confidence that changing precipitation is altering hydrological systems, affecting the quality and quantity of water resources. This will impact urban water supply systems; and even now, whether it is linked to climate change or not, many cities in the world suffer from prolonged or severe droughts. The Millennium Drought in Australia (Van Dijk et al., 2013), California's worst drought in 1200 years (Griffin & Anchukaitis, 2014), and the exceptional drought in south-eastern Brazil that started in 2014 (Stedman, 2014) are just a few examples of recent droughts impacting urban water supply.

A risk approach is advocated in dealing with droughts, as with other natural hazards such as floods and earthquakes (Kampragou, Apostolaki, Manoli, Froebrich, & Assimacopoulos, 2011; OECD, 2013; UNISDR, 2009b; Wilhite, 2011). Since risk is understood as the combination of probabilities and consequences, drought risk management requires a mix of measures that together limit the probability as well as the consequences of water shortage to an acceptable level. Drought risk management is a process aimed at taking measures well in advance of a

CONTACT Joost Buurman joost@nus.edu.sg
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drought event. Several authors have observed that when faced with a drought, authorities take measures in an ad hoc manner, which can be characterized as emergency response or crisis management (Fu, Svoboda, Tang, Dai, & Wu, 2013; Rossi & Cancelliere, 2013; Wilhite, Sivakumar, & Pulwarty, 2014). Although planning and implementing such short-term measures may be effective to reduce immediate drought impacts, in the long run and in the face of climate change, solely relying on crisis management may not be sustainable. Proactive drought risk management is therefore promoted over reactive emergency management.

Urban drought risk management plans should also be evaluated on how they deal with uncertainty. The design of water supply systems is surrounded by uncertainties such as the impact of economic growth on water demand and statistical uncertainty about return periods of extreme events. To avoid extreme consequences from drought events with a small but largely unknown probability, plans and measures should be evaluated on how they affect robustness to extreme drought events. Cities that depend on engineered water supply systems can be considered robust for droughts if socio-economic impacts of water shortage are limited for a large range of plausible drought events, including those that exceed design standards (Mens, Gilroy, & Williams, 2015).

This article aims to explore how cities can do better in reducing the risk of water shortage and improve drought risk management. First, various existing classifications of drought risk management measures are combined and adapted for this study. This classification is then used to compare 10 cities by the type of measures they have taken to deal with (potential) water shortages due to droughts. A classification of drought measures can support the development of a drought risk strategy that consists of an appropriate mix of measures. Better understanding of strategies and measures can inform policy makers on how to design robust water supply systems and drought risk management plans, taking into account the different location and context-specific circumstances their cities face.

Many frameworks, concepts and guides exist to assist the development of drought plans (e.g. HMNDP, 2013; MEDROPLAN, 2007; Rossi, 2000; Rossi & Cancelliere, 2013; UNISDR, 2009b; Wilhite et al., 2014). Although most classifications provide inspiration for drought plan development in general, they have not been placed specifically within the context of risk management. Furthermore, cities have received much less attention in the drought literature, although cities with extensive engineered water supply systems and growing populations become increasingly vulnerable to droughts, and impacts are potentially catastrophic. This article contributes to the existing literature by explicitly linking to risk management and by focusing on cities.

The outline of this article is as follows. The next section discusses drought in the context of urban water supply. Subsequently, a classification for drought measures is developed that is linked to risk management, and which is used to analyze 10 cities that recently faced a drought. The discussion highlights the similarities and differences between the cities. The article concludes with the main findings and recommendations for robust urban drought risk management.

Urban drought risk management

In many cities complex water supply systems support large urban populations, which have few alternative supply options in case of a drought. In recent years in the case studies described later in this article there have been several occasions when consumers depending on urban water supply systems faced water shortages, for example in the Kuala Lumpur area in Malaysia, Sao Paulo in Brazil and Chennai in India. Other cities, such as London, San Diego and Sydney, have also had to restrict nonessential water use to reduce potential shortages in economically and socially important sectors. In addition to piped water supply systems, urban consumers may obtain water from other sources, such as private groundwater pumps and wells, mobile water vendors, or direct extraction from surface water. This is more common in developing countries, where cities have less developed piped water supply systems (e.g. Srinivasan, Gorelick, & Goulder, 2010).

There is no universally agreed definition of drought, as it is a location- and context-specific hazard (Kallis, 2008; Wilhite, 2011). In a tropical climate a few weeks without rain can be a drought, while in an arid climate a drought might occur only after months or years with below-average rainfall. Droughts originate from a period of below-normal precipitation and may result in water shortage for users (Kallis, 2008; Wilhite & Glantz, 1985). Drought in itself is not a problem, but it may become a problem for water users when the amount of water available from rivers, streams, reservoirs and aquifers is significantly reduced for a longer time. A water shortage may occur, which is a temporary water deficit with respect to demand. Water shortage is different from water stress. Whereas water shortage is considered a temporary situation, water stress occurs when demand is high compared to available supply under normal conditions as well (MEDROPLAN, 2007). A situation of water stress requires structural measures with a long-term effect, such as finding new water resources, making water distribution systems more efficient or reducing water demand on a structural basis. This is regardless of a drought situation, but when water stress in a city is reduced it will be less prone to droughts as there is a larger buffer for extreme situations.

Note that water shortage can have causes other than lack of precipitation, for example technical failure of the water supply system, or water quality issues. Also note that the term 'water scarcity' is sometimes used as a synonym for 'water stress' or 'drought', usually in relation to human-induced demand imbalances (Van Loon & Van Lanen, 2013; WWAP, 2012). This article focuses on droughts in urban areas, where we define droughts as situations of below-average rainfall that require action from water managers to avoid a potential water shortage or to manage an actual water shortage.

In disaster management, risk is defined as the combination of the probability of an event and its negative consequences (UNISDR, 2009a). Drought risk in an urban context is the result of the combination of water shortage hazard and vulnerability of water users. The water shortage hazard is the probability that the urban water supply system cannot meet water demand. The hazard is further characterized by its location, intensity, frequency and duration (Bragalli, Freni, & La Loggia, 2007). The vulnerability is defined as the consequences or impacts of a water shortage and the ability of water users to cope with the consequences. This is determined by a range of social, economic and environmental factors. Hazard characterization is well developed for drought risk analysis: probabilities of water shortage can be determined based on meteorological observations, systems analysis and other methods and data (though data may not always be available). Vulnerability assessment is, however, much less developed, particularly for urban areas (Kallis, 2008). The impacts of a water shortage will differ between different water users, and understanding coping mechanisms requires detailed socio-economic research.

The UNISDR (2009b, p. 10) defines drought risk management as a "systematic approach of using administrative directives, organizations and operational skills and capacities to implement strategies, policies and measures for improved coping capacities in order to lessen, i.e., prevent, mitigate and prepare for, the adverse impacts of drought and the possibility of disaster". The key aspect of a risk management approach to dealing with droughts is that measures are planned in advance. It is considered better if the (sometimes controversial) measures are agreed upon upfront without the immediate pressure of a water shortage crisis. Drought crisis management rather than drought risk management is considered costly because decisions have to be made at the last minute and affected communities largely depend on government support to survive the drought impacts, while drought risk for the long term is often not reduced (Wilhite, 2011). Planning also includes measures that take a longer time to implement, such as measures to increase the buffer between supply and demand, for instance by building new reservoirs or reducing network leakage. Although these long-term measures usually cannot be implemented during a drought (unless it is a long, multi-year drought), the case studies described below suggest that droughts and water shortage situations are often the instigator for long-term measures, such as the desalination plants in Sydney, London, Dalian and Chennai, wastewater recycling in San Diego, and subsidies for water-saving measures in Sydney and San Diego.

How governments plan for and handle a drought situation can affect the severity of drought impacts. As in management of other natural hazards, having a plan in place that includes risk assessment, monitoring and early warning, and response actions will reduce potential impacts and can avert disasters. However, policy makers and water managers are struggling with droughts (Hayes, Wilhelmi, & Knutson, 2004). The wide variety of definitions of drought (Wilhite & Glantz, 1985) makes it difficult to establish trigger points for action. Further challenges are that much information is location- and situation-specific and there are many approaches to drought risk management to choose from. Nevertheless, attention to drought risk management has increased significantly in the past two decades, especially in countries that frequently experience droughts, such as the United States, Australia and Brazil, and many areas have some form of drought management plans in place (Fu et al., 2013; Gutiérrez, Engle, De Nys, Molejón, & Martins, 2014; WMO, 2000).

Urban drought risk management has a clear scope, which is geographically defined by the area where water is abstracted (which can in some cases be far away, especially when inter-basin transfers are involved), stored and distributed, and concerns all water users within this area, including those depending on private wells or other sources. Urban drought risk management is not carried out in isolation, as it interacts with other administrative levels, such as the river basin, province or country.

Classification of drought measures

Many classifications and categorizations of drought measures can be found in the literature (e.g. Dziegielewski, 2003; Rossi, 2000; Werick & Whipple, 1994; Wilhite, 2011; Yevjevich, 1967). Most of these classifications support making drought plans, both on a strategic level (balancing supply and demand) and on a tactical level (reducing impacts during a drought). Classifying measures can help in understanding the extent to which urban areas are moving towards a proactive risk management approach to deal with droughts. Based on a review of existing classifications in the literature and an analysis of drought measures taken by 10 cities (see later in this article), a classification that links to risk management was developed in an iterative process.

Starting with the literature, the most intuitive classification distinguishes between increasing water supply and reducing water demand. Yevjevich, Hall, and Salas (1977) added a third type: minimizing drought impact. This refers to measures aimed at limiting the socio-economic consequences of water shortage. These measures may include public aid to compensate for income losses, insurance programmes and tax reduction (Rossi & Cancelliere, 2013).

A second way of classifying drought measures is by the sector that is affected by the measure. Rossi (2000) distinguishes between measures aimed at the urban, agricultural, industrial and recreational sectors. This article focuses on urban measures, but measures aimed at other sectors (outside the city) may have an effect on urban water shortage. For example, if agricultural water demand is reduced this will increase the total available water for urban use in a river catchment. In this study such measures are included from the perspective of the city.

A third way of classifying drought measures is based on *when* they are implemented. Werick and Whipple (1994) distinguish between strategic, tactical and emergency measures. According to them, *strategic* measures are physical and institutional measures that are planned and implemented in advance of the drought, such as water supply structures and water law. *Tactical* measures are also developed in advance, but implemented when short-term water shortage is expected (e.g. water rationing). *Emergency* measures are developed and implemented during a drought. This classification is in fact based not only on the implementation timing of the measure in relation to a drought event, but also on the planning horizon. Measures that are planned in advance are considered part of proactive drought risk management, as opposed to a reactive approach, where unplanned measures are taken ad hoc (Rossi & Cancelliere, 2013; Wilhite et al., 2014). Dziegielewski (2003) also classifies measures according to timing of their implementation: (1) water supply planning under normal conditions; (2) drought contingency planning for coming droughts; and (3) drought management for ongoing drought. This is comparable to the distinction Werick and Whipple make between strategic, tactical and emergency measures. The classification of Dziegielewski is linked to the planning horizon and lead time, from long term (normal conditions) to short term (ongoing drought). The long-term / short-term classification is also used by several other authors (e.g. Hayes et al., 2004; Wilhite, Hayes, Knutson, & Smith, 2000).

In addition to the three ways of classifying drought measures described above, other functional classifications have been proposed. Wilhite (1993) proposed nine categories of mitigation measures, such as legislative measures, infrastructure efficiency programmes and emergency measures. Fu et al. (2013) classify measures in the United States' state drought plans following the drought risk analysis components proposed by Hayes et al. (2004). The drought risk management component in this classification is further subdivided into seven categories of actions, such as water conservation and supply augmentation.

The various classifications serve different goals in research and practice. Fu et al. (2013) use their classification to assess whether drought plans rely on crisis management or risk management. Their scope of drought management classification is therefore the entire process of planning, monitoring and implementing actions to deal with drought. MEDROPLAN (2007) has a similar scope and provides guidelines for proactive drought management, including short-term and long-term measures; this scope goes beyond drought measures and includes all kinds of planning and organizational aspects, such as establishment of early-warning systems and procedures, resolution of water conflicts, and implementation of plans. This article focuses on drought measures only, and uses our updated classification of drought measures, which is linked to risk management, to structure and compare the drought measures taken by 10 large cities. Comparing existing drought management plans and governance aspects falls outside this scope.

Figure 1 summarizes the main classifications found in the literature. In this figure the classifications are linked to three stages of a drought. The classifications have in common that they distinguish between measures taken before a drought occurs and those taken during a drought. Different terms are used to refer to the type of measures that are planned and implemented before the start of a drought: mitigation planning, water supply planning, long-term, and strategic. They can aim at both supply increase and demand reduction, for example reservoirs and desalination plants, or water conservation and changing garden plant types. In drought risk terminology, these types of measures will increase the reliability of sufficient water supply and thus reduce the probability of water shortage.

The period after the start of a drought can be divided into a phase with visible reduction in water availability (for instance declining reservoir storage) but no actual water shortage yet, and a phase of water shortage. Here, different classifications exist. While Wilhite (2011) and many other authors distinguish only 'before' and 'during' a drought, Dziegielewski (2003) and Werick and Whipple (1994) further divide 'during a drought' into tactical measures that are taken when a drought is recognized, and emergency measures that are taken when a shortage of water exists. Dziegielewski mentions that the three categories overlap to some extent. According to Werick and Whipple, tactical measures are short-term and deal with the residual vulnerability left by strategic measures, whereas emergency measures are responses to circumstances that exceed expectations. Thus, emergency measures are those that deal with unexpected events (in the short term) and are therefore unplanned by definition. They add that some alternatives are on the border of the two categories and that exact classification may not always be needed.

Classifying measures according to timing seems very useful because it shows to what extent regions are well prepared for droughts that are more severe than the design drought. However, when applying such a classification, several issues arise. Firstly, a distinction

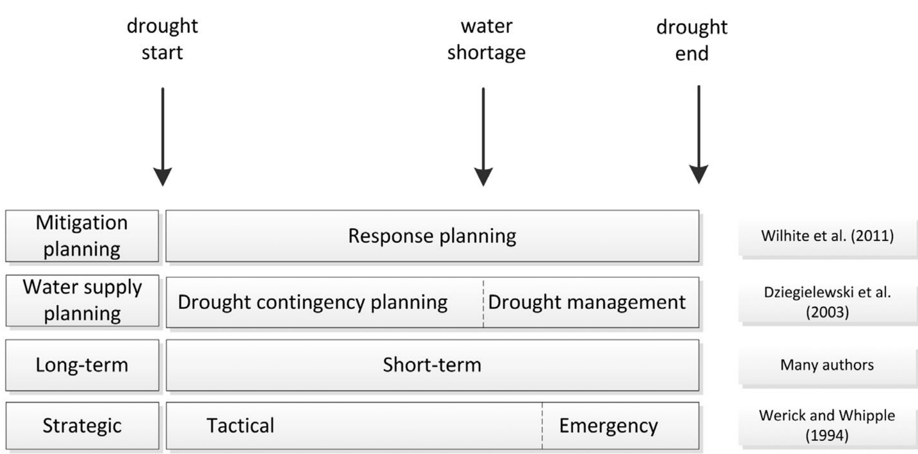

Figure 1. Classifications and timing of drought measures.

between planned and unplanned is difficult to use, as it is not a characteristic of the measure itself: short-term measures implemented during a drought, such as water use restrictions, can be planned in advance, or not. Secondly, long-term and short-term can also refer to the duration of the impact rather than to whether it is planned in advance: a water-saving campaign implemented as an unplanned, short-term emergency measure can have a permanent impact on water use. Thirdly, timing is relative to different measures and different droughts, and a it is continuous scale, which makes it difficult to classify and compare actual measures. For instance, a leak detection and repair programme could be a long-term programme, implemented when there is no immediate drought, or it could be a short-term programme as a reaction to a drought crisis. Thus, we acknowledge the different drought stages for which measures can be planned, but we do not consider 'planned' and 'unplanned' as characteristic of the measure.

A classification of drought measures can provide insight into the extent to which cities employ a mix of drought risk measures. A diversified portfolio of measures reduces the risk of water shortage. In our classification framework we adopt the terminology of Werick and Whipple (1994), but we emphasize that measures are strategic if they have a long-term impact, and tactical or emergency when they have an impact only in the short term:

(1) Strategic measures: long-term impact, mostly planned and implemented in advance
(2) Tactical and emergency measures: short-term impact, implemented during a drought; planned in advance (tactical) or unplanned and ad hoc (emergency).

Note that, as mentioned above, 'planned' and 'unplanned' are not characteristics of measures themselves and are therefore not used as a distinguishing factor in our classification. The difference between tactical (short-term impact, planned) and emergency (short-term impact, ad hoc, unplanned) measures is that they are planned or unplanned; but this fact is case-specific and does not change the nature of the measures. In addition, water managers would not be keen to publicly admit that measures are ad hoc, and hence this characteristic is difficult to observe in case studies. In most cases the available information only allows commenting in qualitative terms on the absence, presence and extent of drought planning in a city. Although we do not distinguish between tactical and emergency in our classification, we still think it is important to acknowledge that there exists an emergency phase. A city can prepare for this by organizing emergency teams with clear responsibilities. They can then decide on ad hoc emergency measures.

As the second dimension we distinguish between supply increase, demand reduction, and socio-economic impact reduction, similar to the work by Yevjevich et al. (1977). The two dimensions result in the six categories shown in Table 1. A long list of measures in each category is provided in the Appendix 1. Socio-economic impact reduction contains the measures that do not directly affect supply or demand, such as income loss compensation, insurance

Table 1. Classification of drought measures.

	Supply increase	Demand reduction	Socio-economic impact reduction
Strategic: long-term impact, implemented in advance	SSI: Strategic Supply Increase	SDR: Strategic Demand Reduction	SIR: Strategic Impact Reduction
Tactical/emergency: short-term impact, implemented during drought	TSI: Tactical Supply Increase	TDR: Tactical Demand Reduction	TIR: Tactical Impact Reduction

programmes and tax reduction. These measures address the impacts of a water shortage rather than the water shortage itself. All measures found in this category (see Appendix 1.) are economic in nature, addressing household or company income shortfalls due to droughts.

For classification purposes, we focus on the primary objective of each measure. Drought measures sometimes have more than one effect. For instance, increasing supply by drilling additional groundwater wells can have secondary socio-economic impacts if it saves households from having to buy expensive bottled water. For long, multi-year droughts it is possible that strategic measures are implemented during a drought; e.g. new, permanent wells could be drilled and commissioned during a drought, and voluntary water-saving campaigns could lead to a permanent reduction in water demand. Hence, in using our classification for the 10 cities in the next section, the first criterion for considering a measure strategic or tactical is long-term versus short-term impact, while implementation in advance versus implementation during drought is secondary. In the case where a strategic measure is implemented during a drought, this will be mentioned separately.

This classification of drought measures links well to disaster risk management, which will now be demonstrated. Urban drought risk management is about reducing the probability of water shortage as well as reducing the impact of this water shortage. In Figure 2 these two dimensions are depicted along the horizontal and vertical axes, respectively, with an imaginary risk curve. The risk curve represents the possibility that events with a low probability (extreme droughts) have a high impact, and vice versa. The classification developed above is based on timing (strategic, tactical/emergency) and the supply/demand/impact dimension.

Regarding timing (Figure 2a), strategic measures are designed to prevent water shortage with a certain return period. Planning of water supply systems is based upon an assessment of frequency of events with a magnitude and extent. This is comparable to metrics of water supply reliability (i.e. probabilities of water shortage). Hence, strategic measures aim at reducing the probability of water shortage. Some strategic measures reduce the impact of water shortage, for instance insurance. Tactical and emergency measures are designed for the more extreme events, and implemented only during a drought when the strategic design standard is exceeded. This type of measures will thus reduce the impact part of risk.

Strategic, tactical and emergency measures may increase supply or reduce demand. However, within the category of strategic measures, supply increase affects only the probability part of risk, as a strategic supply increase reduces the probability of a water shortage (Figure 2b). A strategic supply increase (having more water available) does not affect the impacts of a water shortage when this water is not available, and hence strategic supply increase does not reduce impacts; it takes a more severe drought before the impacts materialize. In contrast, demand reduction affects both the probability and the impact of risk: lower demand increases the buffer between supply and demand and hence reduces the probability of a water shortage, while reducing water use, for instance conversion to low-water-use gardens, also reduces vulnerability and hence the impacts of a water shortage. Supply-increase and demand-reduction measures within the tactical/emergency dimension are aimed at reducing the consequences when a drought is already happening, so they only affect the impact part of risk (Figure 2c). Socio-economic impact reduction measures obviously only affect the impact part of risk.

Summarizing, a mixture of supply, demand, and socio-economic impact measures is important as part of risk management, because this will provide a sustainable balance between supply and demand, and at the same time avoid unacceptable impacts from

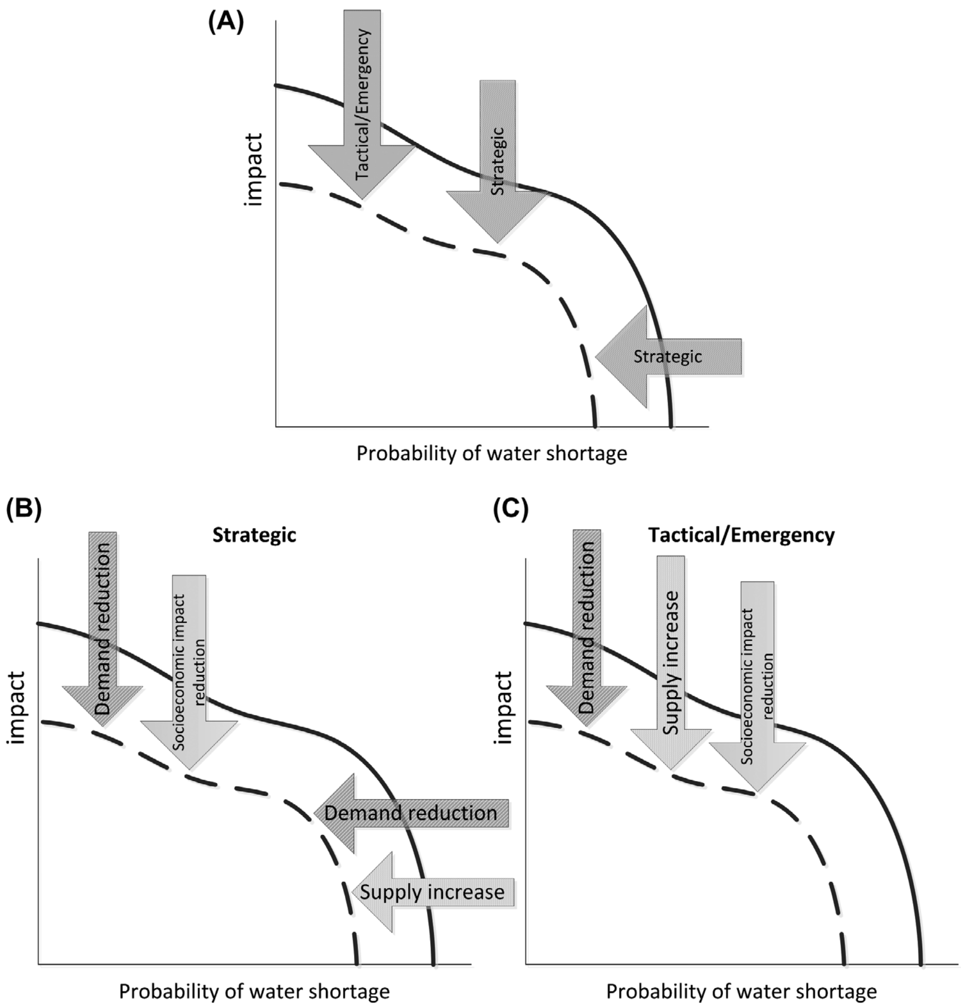

Figure 2. Linking classification of measures with urban drought risk management.

extreme, low-probability drought events (Mens et al., 2015). A mixture of strategic and tactical measures is important to obtain a good long-term balance between demand and supply (strategic) and simultaneously be able to reduce drought impacts from extreme events that exceed the design standard (tactical/emergency).

Case study selection and summary of results

This study compares measures taken by 10 cities that recently faced a drought to distil lessons for urban drought risk management. Information on measures and more generally on how the cities managed the drought was collected through a review of public, on-line media sources. The measures taken by the cities were classified following the classification framework described above.

The 10 cities were selected using multiple sources of information and criteria, as no global database or systematic information on drought-affected cities has been collected, to the

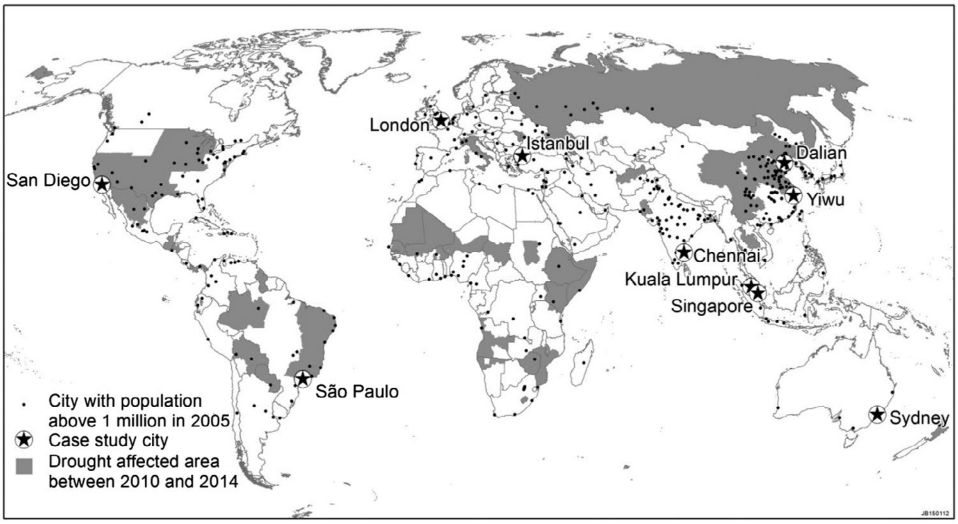

Figure 3. Map of regions affected by drought between 2010 and 2014 and cities with a population of more than 1 million in 2005.

authors' knowledge. The selection procedure was as follows. First, the EM-DAT database (Guha-Sapir, Below, & Hoyois, 2014) was consulted to obtain all recorded drought disasters between 2010 and 2014. The disaster area names in the EM-DAT database were matched with a world administrative boundary map (obtained from http://www.gadm.org), where in a few cases additional information on the disaster was used to link a geographic indication (e.g. "north and north-west regions") with administrative regions. Figure 3 shows the drought-affected areas. Note that the spatial boundaries of a drought generally do not coincide with administrative boundaries; hence the map is an approximation. Cities in the drought-affected areas with more than 1 million inhabitants in the urban agglomeration were selected using a GIS analysis with UN world population data (obtained from https://nordpil.com/resources/world-database-of-large-cities/). This resulted in a list of 11 cities in Russia, 11 in Brazil, 19 in the US, 32 in China and 18 in the rest of the world. The EM-DAT database only covers drought disasters. A disaster will be included if at least one of the following is true: 10 or more people reported killed; 100 or more people reported affected; declaration of a state of emergency; or call for international assistance. For other droughts that may impact the operations of urban water supply systems and result in drought measures but are not included in the EM-DAT database, additional sources (Munich Re NatCatService annual maps [http://www.munichre.com/natcatservice], Factiva news search, Internet search, authors' recollection) were used to identify an additional 10 cities, of which 5 were in Australia. This resulted in a total list of 102 cities in areas that had experienced a drought. Some of these cities experienced a water shortage; some had to take drought measures but did not directly experience water shortage; and some may not have taken any measures even though they were located in drought-hit areas because the urban water supply system had enough storage capacity to handle the drought.

From the 102 identified cities, 10 were selected to study in depth (Figure 3). The selection was done in such a manner that the resulting cities represented as much as possible different levels of development, different climatic conditions, and different levels of water stress as determined by McDonald et al. (2014, Table S1) or water risk as determined by the Aqueduct Water Risk Atlas (http://www.wri.org/our-work/project/aqueduct/aqueduct-atlas). McDonald et al. (2014) use two models for surface water stress and one model for groundwater stress. A city is water-stressed if one or more of the three models indicate water stress. Aqueduct calculates a multidimensional water risk index that comprises physical risk quantity, physical risk quality, and regulatory and reputational risk; for the purpose of this study the weight for flood risk occurrence was set to very low. Table 2 shows that the two indicators of water stress do not always coincide. An additional, implicit criterion was that the required information had to be available in the public domain. For cities where English is not the main language, except Istanbul, an effort was made to search for information in the native language of the city in addition to relying only on English media. Due to limited availability of public information, the final set of 10 cities, as presented in Table 2, does not include any cities in the lowest income category (mostly in Africa) or any in Russia or Central America.

Although the selected cities are not a representative sample in any statistical sense, they can provide insights into how different types of cities under different climatic and water resource conditions deal with droughts. Also, the severity of the droughts experienced by these cities differs considerably, which may to some extent also impact the measures taken. Comparing cities is, however, challenging, as drought impacts and hence measures taken are very context-specific. Hence, this article reviews the measures but does not specifically aim to rank cities or determine which city has better drought risk management.

For each city a thorough search on all information about the drought was carried out, and a systematic description of the context, the physical water supply system, the organization and legislation of water supply, and drought measures was prepared. People with good local knowledge of the water situation in Sao Paulo, Istanbul, Chennai, San Diego, Kuala Lumpur, Sydney and Singapore checked the respective systematic descriptions, and only minor discrepancies that did not impact any of the conclusions were found and accordingly adjusted. Table 2 gives a very brief description of the drought and drought measures in each city. (The Internet data sources used in this study are listed in the online supplemental data at 10.1080/07900627.2016.1138398.)

Each of the drought measures found was classified, and a qualitative assessment of drought planning was made. Classification of drought measures was done following a long list of measures as provided in the Appendix 1. This list was compiled from literature and case-study sources. It should be noted that more public information may be available for some measures than for others; for instance changes in reservoir operation may not be reported in the media. This could give some bias to the results, which are shown in Table 3. In total, 49 measures were found. In none of the cities were any measures found that directly address socio-economic impacts. A qualitative assessment of drought risk planning is provided in the last column. Most cities seem to plan for droughts, with three cities having extensive drought plans in place. For five other cities references to planning in newspaper articles and government documents were found.

Discussion

In total, 31 tactical/emergency and 18 strategic measures were found. Thus, the majority of the measures seem to be implemented during the drought. This could point towards support

Table 2. Overview of case studies.

City	Income level of country[a]	Climatic zone[b]	Water stress[c] | water risk[d]	Approx. drought period	Severity	Brief description of drought	Main measures taken
Chennai, India	Lower-middle	Aw: tropical savannah (wet and dry)	Stressed | high	2012–14 (and 2003–04)	Monsoon 20–23% below normal (and worst in 400 years)	Chennai regularly experiences droughts. In 2003–04, it suffered a crippling water crisis, forcing city residents to rely primarily on expensive imported water brought in by tanker trucks. Recent drought was less severe, but still had significant impacts.	- Temporary supply increase through groundwater wells and mobile tankers - Desalination and new reservoirs, initiated during 2003–04 drought - Some reuse of sewage water -Enforced rationing, shutting down piped water supply
Sao Paulo, Brazil	Upper-middle	Cfa/Cwa/Cwb: temperate with hot summer, dry winter	Not stressed | medium to high	2014, following three dry years	Worst on record	In rapidly growing Sao Paulo the balance between water supply and demand is adequate under normal circumstances, but leaves very little room to accommodate shocks like a major drought. Water rationing is politically sensitive.	- Drawing dead storage from reservoirs - Temporary discounts on water bills - Reduction of network pressure to reduce water losses - Strategic measures such as inter-basin transfers, improving efficiency
Istanbul, Turkey	Upper-middle	Csa: temperate, hot and dry summer	Stressed | high/ medium to high	End of 2013 to summer 2014	Worst in decades	Authorities initially stated in public that there was no water crisis, but later urged people to conserve water when the situation became more severe. Enforced water rationing was avoided for political reasons	- Encouraging people to use less water - Water transfers from surrounding cities - Several strategic supply increase projects (dam, tunnels), but already part of long-term planning
Yiwu, China	Upper-middle	Cfa: temperate, without dry season, hot summer	n/a | high	2013	40% of the reservoirs had been used up	Yiwu has a history of droughts and is in a situation of water stress.	- Water trading with neighbour city - Cloud seeding - Water rationing - Structural water diversion project - Administrative simplification for water equipment subsidies
Dalian, China	Upper-middle	Dwa: cold, dry winter, hot summer	Stressed | medium to high	June–August 2014, following several dry years	Worst since 1951	Dalian experienced periods of drought since 1999, with the drought in 2014 being the worst since 1954. Rapid growth also contributes to water stress and shortages.	- Encourage water recycling and apply water quotas - Promote seawater use and desalination for industries - Promote use of water-saving equipment - Water conveyance projects - New progressive water tariffs

Kuala Lumpur, Malaysia	Upper-middle	Af: tropical rainforest	n/a | high	February–April 2014	Worst since 1998	Kuala Lumpur is a tropical city that normally receives abundant rainfall throughout the year. However, dry periods can occur, and in early 2014 a water shortage arose in the Klang Valley, which is the urban area that includes Kuala Lumpur.	- Extensive water rationing, affecting more than 700,000 households - Cloud seeding - Use of the media to encourage people to use less water - Temporary pipeline
London, UK	High	Cfb: temperate, without dry season, warm summer	Stressed | medium to high	Early 2012, following two dry years	Worst since 1976	London is usually not associated with droughts. However, South-east England is water stressed, and droughts are a relatively common feature of the climate of the UK (recurrence every 5–10 years), usually during summer.	- Temporary increase in desalination production - Use of an artificial aquifer - Voluntary and enforced conservation
San Diego, USA	High	BSk: steppe-cold or Csa/Csb: temperate dry/hot/warm summer	Stressed | medium to high	Since April 2013, following two dry years	Worst on record	San Diego is experiencing the worst drought on record; it started around April 2013, but dry conditions have prevailed since January 2011	- Wastewater recycling - Increase in desalination capacity - Conservation messages through the media - Water use restrictions - Support for garden conversion
Singapore	High	Af: tropical rainforest	Stressed | high	Mid-January to mid-March 2014	Worst on record since 1869	Singapore is a tropical city state that normally receives abundant rainfall throughout the year, but from mid-January to mid-March 2014 some areas received less than 1 mm of rain.	Singapore has put in place a large number of strategic measures to achieve self-sufficiency; hence no additional measures were needed - Some stimulation of voluntary water conservation
Sydney, Australia	High	Cfa/Cfb: temperate, without dry season, hot/warm summer	Not stressed | medium to high	2002–2007, 2012	One of the most severe since 1900	Between 2002 and 2012 Sydney experienced one of the most severe, widespread and prolonged dry periods since 1900.	Having a history of droughts, Sydney has one of the most carefully planned and advanced water management systems. Some measures include: - Water transfers - Progressive water restrictions - Voluntary water use targets - Temporary desalination boost - Water recycling

[a]Source: http://data.worldbank.org/about/country-and-lending-groups. [b]Köppen zones as reported in Peel, Finlayson, and McMahon (2007).
[c]McDonald et al. (2014). [d]Source: Aqueduct Water Risk Atlas (http://www.wri.org/our-work/project/aqueduct/aqueduct-atlas), with default weights except for flood risk set at lowest weight.

Table 3. Summary of classification of drought measures taken by 10 cities.

	Strategic			Tactical/emergency			
City	SSI	SDR	SIR	TSI	TDR	TIR	Planning[b]
Chennai	2	1	0	3	1	0	−/+
Sao Paulo	1	0	0	2	2	0	−
Istanbul	0	0	0	1	2	0	+/−
Yiwu	2	1	0	1	2	0	+/−
Dalian	3	1	0	0	2	0	?
Kuala Lumpur	0	0	0	2	2	0	?
San Diego	0	2	0	0	3	0	+
London	2[a]	0	0	0	2	0	+
Singapore	0	0	0	1	1	0	+/−
Sydney	1[a]	2	0	2	2	0	+
Total	11	7	0	12	19	0	

[a]Includes strategic measures that are employed tactically and hence could be categorized under both SSI and TSI.
[b]Key: ?: no reference to drought risk planning found; −: no drought risk planning present; +/−: some drought planning present, but no indication of a clear drought risk management plan; +: drought risk management plan present.
Note. SSI: strategic supply increase; SDR: strategic demand reduction; SIR: strategic socio-economic impact reduction; TSI: tactical/emergency supply increase; TDR: tactical/emergency demand reduction; TIR: tactical/emergency socio-economic impact reduction.

of the findings of several authors (e.g. Fu et al., 2013; Rossi & Cancelliere, 2013; Wilhite, 2011) that drought management in most cities is reactive (unplanned) rather than proactive (planned). However, in reality the situation is more complex. Tactical measures can still be planned in advance. The planning column in Table 3 shows indeed that most cities seem to have some kind of planning for droughts, which would point towards a proactive approach. Most cities thus seem to plan to some extent for droughts, but focus on implementing measures during the drought. Note that Table 3 may give the false impression that strategic measures are lacking, while in reality they may be already in place. Because these types of measures are usually not taken during a drought and can also be part of the overall design of the system, they may not appear in our analysis of recent droughts and water supply systems. This is for instance the case for Singapore, which has put in place a large number of strategic measures to become self-sufficient in water supply (because part of the water is currently imported from neighbouring Malaysia), and hence has a highly efficient, robust water supply system. Directly related to the worst drought on record, no strategic measures are reported. A water shortage could be avoided by increasing desalination and water recycling production and relying on reservoir storage. Similarly, Sydney has one of the most carefully planned and advanced water management systems. Strategic water conservation strategies have been a norm while the city constructs its water management system, centring on the idea of a 'drought-proof' or 'climate-proof' city and integrated water management methods that focus on the expansion of supply portfolios. Some of the strategic measures may not appear in Table 3 as they may not have been reported in relation to the drought.

Having a mixture of long-term and short-term (strategic and tactical/emergency) measures is important to deal with the natural variability of droughts: strategic measures are designed for relatively frequent droughts, while tactical measures are for more severe situations. Tactical and emergency measures are usually too expensive to be used on a structural basis (e.g. trucking of water, or utilizing agricultural wells for drinking water), but they can reduce impacts under extreme conditions. Too many strategic measures can lead to a water supply system with over-capacity, which can also be expensive to build and maintain. Based on the 10 cases it is not easy to judge how well the cities employ this mixture, because only measures taken during, or directly related to the drought are reported in Table 3. However, reflecting on the case studies in more detail provides some additional insights. Cities in high-income countries, such as London, Sydney and Singapore, often take tactical measures during drought, because the strategic measures have already been taken care of. For instance, the city-state of Singapore has a sophisticated water supply system consisting of reservoirs, desalination, water reuse and water imports from Malaysia, and applies several demand-reduction measures, such as subsidies and legislation on water-saving devices and awareness campaigns, which address the water-stress situation and significantly reduce the probability of water shortage. London has a desalination plant and an artificially recharged aquifer which were purposely built for droughts. Sydney has a desalination plant that can boost its capacity during droughts. Hence, when faced with a drought these cities have a clear set of temporary, tactical options: use of desalination or the artificial aquifer; and voluntary and enforced conservation. The region of which London is part has a comprehensive drought plan in place, which describes the actions to take during different stages of a drought (Environment Agency, 2012). A severe, multi-year drought may be a stimulus to undertake additional strategic measures, such as in San Diego, which implemented water-saving measures aimed at gardens and accelerated a water reuse project, and Sydney, which implemented measures for private rainwater collection and public water recycling. Similarly, some of the cities in middle-income countries took strategic measures during the drought. Sao Paulo tried to accelerate expansion of water supply schemes with inter-basin transfers; the 2003–04 drought in Chennai initiated the construction of a desalination plant and new reservoirs; Yiwu embarked on a water diversion project; and Dalian promoted the structural use of seawater and desalination for industries and water-saving equipment. This is probably related to the fact that water demand has grown rapidly due to population growth in these cities, leading to water stress. It shows that these cities became aware of their situation of water stress under normal conditions and the recent drought is a motivation to take structural measures. Because these structural projects have a long implementation time, tactical measures were also needed to deal with the current drought. Thus, some (developed) cities already have strategic measures in place and therefore focus on tactical measures during a drought, while other (developing) cities take both tactical and strategic measures during a drought, because the drought is an incentive for action.

In addition to a mixture of strategic and tactical/emergency measures, a mixture of supply and demand measures is important to avoid low-probability, high-consequence events (Mens et al., 2015). The response to increased demand is often to build larger reservoirs and more infrastructure to transport water over longer distances. This is apparent in the Sao Paulo case, where the population has increased from about 17.0 million in 2000 to 21.1 million in 2015 (United Nations, 2015) and where strategic measures focus on supply increase through expansion of the supply schemes. Similarly, in Chennai, the population grew from 6.3 to 9.9 million between 2000 and 2015 (United Nations, 2015). One of the projects inaugurated in 2004 draws water from a lake 225 km south of the city. However, when droughts do occur they have a greater impact, affecting larger areas and more people. Referring back to Figure 2, supply increase reduces only the probability of water shortage, not the impact.

Most demand-reduction measures found are taken temporarily (tactical/emergency), whereas supply increase is mostly done with large infrastructure projects (strategic). Most cities use the media to broadcast water-conservation messages. Focus on strategic demand reduction, for instance through water recycling and changing water tariffs, can be found in only a few cities, such as Dalian, Singapore and Sydney. Another observation from Table 3 is that for tactical and emergency measures, cities in high-income countries focus more on demand-reduction measures than cities in middle-income countries. An exception is Sydney, where a range of tactical measures is available for both supply increase and demand reduction, for example drought restrictions, water transfers, groundwater extraction, and voluntary water use targets. Developing cities could have fewer opportunities for demand reduction than developed cities, because their per capita consumption can be lower. For instance, 2005 consumption in Chennai was 97 litres per capita per day, while for Singapore in 2007 it was 158 litres per capita per day (http://www.ib-net.org). Water consumption in lower-income cities just meets basic needs, while in high-income cities more water is used for non-essential uses such as gardening, car washing, etc. However, this is very city-specific; for instance Sao Paulo has a relatively high consumption per capita, around 230 litres per day (http://www.ib-net.org). Another reason might be that the high-income cities in our sample have more developed water supply systems with less (relatively) easy options for additional supply in case of drought, as most options have been implemented already. San Diego is an example where additional supply would require long-distance inter-basin transfers or desalination. A final reason may be a link with governance: in the developed cities in our sample, enforcement of demand-reduction measures may easier to carry out than in the less developed countries.

In none of the cities were any measures to directly reduce socio-economic impacts found, such as relief programmes or insurance schemes. This is very different from rural areas, where such measures are common. The governments of Australia and the United States have implemented large relief programmes for farmers, and during the drought in Tamil Nadu (Chennai) farmers also received assistance in the form of fodder supply. Generally speaking, the variety of strategic, tactical and emergency measures that cities employ during droughts seems rather limited.

A final interesting observation from the case studies is about the way politicians deal with droughts. Water rationing can be politically sensitive. In Sao Paulo mention of the 'water crisis' was avoided due to elections, and for a long time politicians publicly rejected any notion of a drought problem. Similarly, in Istanbul the authorities initially stated in public that there was no water crisis during a severe drought in the summer of 2014, though they later urged people to conserve water when the situation became more severe. This reaction to droughts could hamper effective drought risk management.

The classification presented in this article could help cities identify a suitable mix of measures. Although the classification was developed for cities, it can be generally applied to other areas and sectors as well. The risk approach for droughts is equally valid for instance for agriculture or at the river basin level. It provides a good basis for discussing a variety of measures, and eventually the proposed mix of measures should be evaluated on its cost, degree of risk reduction, robustness to extreme events, and environmental effects. Methods for quantitative drought risk analysis are therefore needed to support the development of a comprehensive drought risk management plan.

Conclusions

Urban areas have to deal with the risk of water shortage due to droughts. The literature suggests that many cities take a reactive approach to drought management, which means that these measures are unplanned and do not help reduce the long-term water shortage risk due to drought. This article lists drought measures that 10 cities have taken during recent droughts, and classifies these measures under strategic or tactical, and under supply increase, demand reduction or impact reduction. The results show that many cities do take drought measures during a drought, but this does not mean that their approach is only 'reactive'. In fact, high-income countries have strategic measures already in place and therefore focus on tactical measures when a drought does occur. The cities in middle-income countries show that droughts are often a catalyst for new strategic measures that address water stress in the long term. In other words, their approach may be reactive, but when they decide on strategic measures the risk of water shortage due to drought will be reduced. Although 10 cities constitute only a small subset of all cities that faced a drought in the selected period, we have attempted to analyze a cross-section of different cities, and we expect that the conclusions would not be substantially different for other cities.

The proposed classification is linked to the risk approach commonly applied in disaster risk management. It shows to what extent cities employ a mix of measures in two dimensions. The first dimension is supply / demand / socio-economic impact; this is important because supply measures only reduce the probability of water shortage, demand measures reduce both probability and consequences, and impact measures (such as insurance) reduce the consequences. Together, they help reduce the risk to an acceptable level. The second dimension is strategic / tactical-emergency; this is important because strategic measures have a long-term impact on risk, and tactical and emergency (temporary) measures further reduce consequences for the more extreme drought events. Both types must be planned beforehand.

Using the classification of drought measures developed in this article we find that the variety of measures the cities employ during droughts seems rather limited. For example, most tactical and emergency measures are focused on demand reduction, whereas most strategic measures are focused on supply increase. Although this is also strongly related to what is technically and practically possible in a country, cities could improve the mix of measures. A classified long list of measures could provide inspiration to discuss alternative ways to deal with water shortage. Because in this article only measures taken during recent droughts were studied, the list per city was not complete. It may for instance give the false impression that cities do not employ strategic measures, while in reality these measures are already in place. To obtain a better overview of measures in future studies, we thus recommend also examining the current water supply system and existing drought management plans. The classification could be used by cities to develop or assess their own drought risk management plans and by decision analysts to advise on where cities can do better in terms of proactive risk management and the mix of measures that results in a robust drought risk strategy. Although comparison of cities is difficult due to differences in drought and other characteristics, the classification and analysis of case studies could serve as a framework and example for cities developing drought risk management plans.

Disclosure statement

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Appendix 1. Long list of categorized measures

Category	Measure
Strategic supply increase	
Improving existing supply system	Increasing reservoir storage
	Improvement of distribution system (supply network) efficiency
	Recharging groundwater reserves
	Reforestation
	Recirculation of water
	Leak detection and repair
Utilizing/constructing new supply sources	Drilling wells
	Constructing reservoirs
	Building desalinization plants
	Utilizing groundwater storage
	Agricultural wells
	Inter-basin and within-basin water transfers
Reallocation among users	
Tactical/emergency supply increase	
Adapting the existing water supply system	Temporary recirculation of water
	Reservoir evaporation suppression
Emergency supply sources	Trucking water
	Temporary pipelines
	Utilizing reservoir dead storage
	Utilizing (low-quality) ponds
	Hiring agricultural wells
	Reactivation of unused wells and increasing capacity of existing wells
	Temporarily increasing desalination plant capacity
	Emergency water transfers / water banking
Temporary prioritization	Reduction of hydropower releases
	Withdrawal from recreational lakes
	Relaxation of environmental flow requirements
Meteorology management (precipitation and evaporation management)	Cloud seeding
Strategic demand reduction	
Urban water conservation	Dual distribution network for urban use
	Economic incentive for private investments
	Water recycling systems
	Voluntary water conservation
	Enforced water rationing
	Adjusted water pricing structure
Agronomic or industrial techniques	Dry crops instead of irrigated crops
	Sprinkler or drip irrigation
Tactical/emergency demand reduction	
Water service restrictions	No new customers
	Discontinuation of sale to water hawkers
Temporary water conservation (voluntary)	Voluntary water saving (such as restricting non-essential use)
	Emergency conservation (home water audits, plumbing retrofits, industrial audits)
Water rationing (enforced)	Odd/even day supply, per capita allocation
	Emergency water pricing
Urban water conservation	Temporary relaxation of legislation on reuse of water
Strategic socio-economic impact reduction	
Insurance	Private-sector insurance
	Government or donor-funded insurance
Financial	Schemes to help water-dependent companies manage fluctuating cash flows in wet and dry years
Tactical/emergency socio-economic impact reduction	
Government relief programmes	Direct income support
	Taxation measures
	Concessional loans