Water Resour Manage (2016) 30:4913–4926
DOI 10.1007/s11269-016-1461-0

Overcoming Urban Water Insecurity with Infrastructure and Institutions

Julie C. Padowski[1,2] · **Lorenzo Carrera**[3,4] ·
James W. Jawitz[5]

Received: 7 June 2016 / Accepted: 1 August 2016 /

Abstract Urban growth and development depends on both the local hydrologic conditions and how water resources are procured and managed. The objective of this study was to assess the water security of large urban areas based on their physical hydrology, existing water supply infrastructure, and water management institutions. This study examined 108 large cities (>750,000 people) in the United States ($n = 50$) and Africa ($n = 58$), encompassing a broad range of hydrologic and socio-economic conditions, including degrees of institutional complexity. Urban water availability was estimated as the volume of water available from local, natural water sources, as well as water captured via infrastructure such as reservoirs, wellfields, or water transfers. Urban institutional complexity was assessed based on ability to provide, regulate and maintain urban water supplies. Over half of the cities in this study rely on captured water to meet urban demands and maintain high levels of institutional complexity in doing so. Cities able to adequately supply water from local natural sources (37 %) maintain significantly lower institutional complexity than cities using water captured from non-local sources. Cities categorized as water insecure (7 %) had minimal access to either local or captured water resources and operated using the simplest water institutions. Results suggest that low local availability drives the urban response for capturing additional water supplies,

---

Electronic supplementary material The online version of this article (doi:10.1007/s11269-016-1461-0) contains supplementary material, which is available to authorized users.

✉ Julie C. Padowski
julie.padowski@wsu.edu

[1] State of Washington Water Research Center, Washington State University, Pullman, WA 99164, USA

[2] Center for Environmental Research, Education & Outreach, Washington State University, Pullman, WA 99164, USA

[3] Fondazione Eni Enrico Mattei, Isola di S. Giorgio Maggiore 8, 30124 Venice, Italy

[4] Euro-Mediterranean Center on Climate Change, Isola di S. Giorgio Maggiore 8, 30124 Venice, Italy

[5] Soil and Water Science Department, University of Florida, PO Box 110290, Gainesville, FL 32611, USA

and is both the cause and product of more complex institutional frameworks. Efforts to address urban water insecurity should focus more attention on meeting not only the physical but managerial needs of a city.

Keywords Urban water · Water supply · Water insecurity · USA · Africa · Water institutions

1 Introduction

Freshwater is fundamental to the well-being of the human population, more than half of which now resides in urban areas (United Nations, 2014). Not all urban areas are proximal to freshwater resources, but heavy investment in large-scale hydraulic infrastructure, such as aqueducts, dams, and well fields, has allowed many urban areas to develop water systems for transferring, storing, and regulating water resources thus overcoming water insecurity issues associated with urban growth and/or geography (Bettencourt et al., 2007; McDonald et al., 2014; Padowski and Jawitz, 2012).

Despite these infrastructural solutions, urban water insecurity remains a concern for many cities (Grey and Sadoff, 2007; Jenerette and Larsen, 2006; McDonald et al., 2011; Proença de Oliveria et al., 2015). Globally, nearly one-quarter of large cities face water stress due to either physical or economic insecurity (McDonald et al., 2014). Cities also suffer from water security issues related to institutional challenges associated with acquiring and providing water (Kiparsky et al., 2013); yet a comprehensive understanding of how urban water is managed is often missing from large scale availability analyses.

In practice, institutions are difficult to compare, as subjective forces (e.g. cultural paradigms, management choices, political climate) and local conditions (e.g. aridity, geography, hydrology) can create profound differences between systems (Blomquist et al., 2004; Meinzen-Dick, 2007). As such, there are frameworks for evaluating water institutions that vary widely in their approach and focus (e.g., Saleth and Dinar, 2004; Schneider et al., 2015). While assessments of urban water institutions are not uncommon, only a few studies (e.g., van Leeuwen et al., 2012) assess the combined hydrological and institutional sustainability of urban water systems, but rarely perform such analyses at the regional, national or global levels. Rather, previous works tend to focus either on a limited number of specific systems (e.g., Jacobsen et al., 2012; Lundqvist et al., 2005; Scholz and Stiftel, 2005), or primarily the hydrological (McDonald et al., 2014; Showers, 2002) or institutional (Brown et al., 2009; Estache and Kouassi, 2002; Nafi et al., 2015; Pierce et al., 2011) aspects of urban water.

This work provides a quantitative, integrated assessment of urban water security as a function of both water availability and water management institutions. Detailed information on the physical hydrology, hydraulic infrastructure, and institutional characteristics of a diverse set of large cities was evaluated to compare the different strategies used by urban areas to obtain and manage water. The richness of this integrated analysis, paired with the broad geographic distribution of urban areas examined, offers new insight into where and why cities may face serious water security threats.

2 Urban Water Security

Assessing current and future resource sustainability requires knowledge about resource quantities (Graedel and Klee, 2002), as well as resource management strategies (Kemper, 2001), especially in areas where hydraulic infrastructure may cross multiple watersheds or groundwater basins, significantly changing the hydrologic dynamics of the basins they tap (Weiskel et al., 2007). In this study, an urban water typology is used to characterize four types of urban availability based on the local hydrology and urban hydraulic infrastructure in place. The institutional characteristics of urban water management systems were assessed using the concept of *institutional complexity*, where the level of complexity acts as a proxy for the degree to which urban water institutions have been able to develop sound and strategic water management practices.

This study examined large cities (>750,000 people) in the United States ($n = 50$) and Africa ($n = 58$) with sufficient availability of hydrologic and urban water management data. Larger cities were selected because of the relatively higher likelihood of publicly available water resources and management data. Africa has been the focus of much recent research on water scarcity (AIDC, 2013; Falkenmark, 1990; Jacobsen et al., 2012; Meigh et al., 1999; Muller, 2007; Showers, 2002; Vörösmarty et al., 2005), which has made available a wide range of data useful for comparing infrastructural and institutional characteristics related to water insecurity. The selected cities therefore encompass a wide range of hydrological settings, and span the global development spectrum. A complete list of cities, availability type, and institutional complexity scores can be found in Table S-1.

3 Methodology

Urban area boundaries were obtained from the US Census Bureau for US cities and Gridded Population of the World (GPWv3) database (CIESIN, 2004; USCB, 2009) for sampled African cities. A 5-km and 10-km buffer was applied to each US and African urban area boundary, respectively, for the purposes of distinguishing local from captured water. Captured water, detailed in the following section, refers to the part of the water supply that is considered exogenous to the urban area. African urban areas were given larger buffers to compensate for coarser data and informal settlements in the outskirts of urban centers, which may have been otherwise missed. All references to the urban area boundary (UAB) include these buffers.

3.1 Water Availability

For each of the 108 cities in this study, water availability was calculated as a function of both hydrologic and hydraulic water sources using the general framework described by Padowski and Jawitz (2012). Local availability represents a baseline mean annual volume of water, Q_L, to which an urban area potentially has access. This type of availability is estimated from naturally occurring, local sources (i.e., rivers, lakes, aquifers) that intersect or border a UAB regardless of whether the supply is actually used as a source of urban water. Not all local water is available for human consumption. Therefore rules for allocating quantities of water (e.g. environmental flow requirements) were also included, although they do not account for source water quality. This local availability metric creates a base scale for assessing water stress. Captured water (hydraulic) availability (Q_C), represents the annual mean additional volume of water collected by an urban area from constructed sources (i.e., reservoirs and wellfields), and/or imported from sources (natural or constructed) outside the UAB via additional infrastructure. The total volume of water available (Q_T) is the sum of the local and captured water availability. As discussed in Padowski and Jawitz (2012), this method seeks to use best available data, however data gaps and limitations (i.e. assumptions about reservoir/groundwater allocations) may affect the accuracy of availability estimates in some cases, especially where data are sparse.

A water availability typology (Fig. 1) was conceptualized to categorize the primary ways in which urban areas use hydraulic infrastructure to meet urban water needs. In this typology, cities with access to ample volumes of water from nearby, naturally-occurring sources reflect a *natural abundance*, or availability of water, and thus would have developed little to no infrastructure to capture additional supplies. In cities subject to physical scarcity of water, where local water sources are insufficient to meet a minimum supply requirement, urban needs would be met through reliance on captured (hydraulic) water collected via storage or long-distance transfer to create *artificial abundance*. In such cases, the total availability exceeds the minimum supply and is comprised of both natural and captured sources. Also identified are cities with access to sources, either naturally or through capture, that are vastly beyond typical requirements providing *super abundance*. Cities subject to physical scarcity without the capacity to capture sufficient additional water are categorized as *water insecure,* with neither natural abundance nor the ability to create adequate water infrastructure to meet urban demands.

Data for US local and captured water availability, including source locations, allocation rules and available volumes, were the same as those used by Padowski and Jawitz (2012) with selected updates, as described in Table S-1. Water supply sources for African cities were compiled using data from the City Water Map (McDonald et al., 2014), Google Earth, and global and regional water databases, and were supplemented with information from individual literature sources and water provider websites (Table S-2). Local and captured African river locations and discharges were taken from estimates of global mean annual river discharge based on the accumulation of local runoff on a 0.5 × 0.5 degree gridded network (Fekete et al., 2002). Environmental water demand estimates for African rivers could not be calculated in a similar fashion to those in the US due to a lack of historical streamflow data and were instead

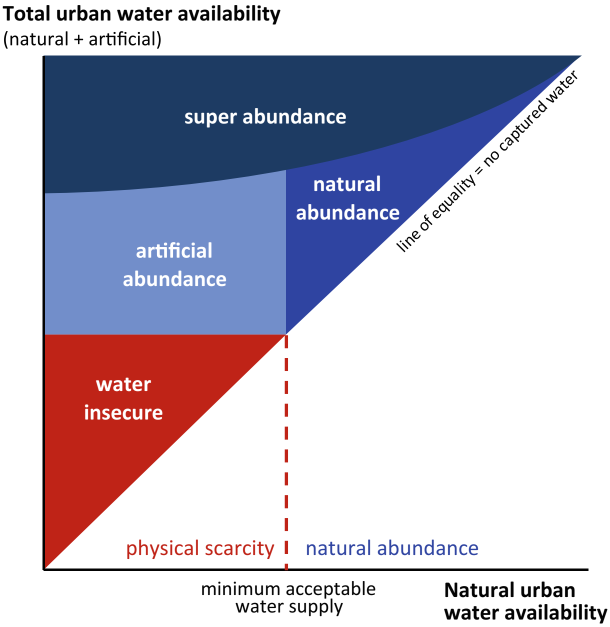

Fig. 1 Urban water availability typology. This conceptual diagram identifies four broad categories representing the different management strategies urban areas use to achieve water security. The total water available is the sum of local and captured sources (y-axis), with the 1:1 line of equality indicating no water available from captured sources. Increased distance above this line indicates larger volumes of water obtained from captured sources

assumed to be 25 % of the mean annual discharge. Available groundwater for African cities was estimated similarly to US cities, but relied on hydrogeological data from regional maps reporting aquifer area and saturated thickness (MacDonald et al., 2012) The mean annual volume of water available to African cities from natural lakes and constructed reservoirs was quantified similarly to those of US cities using data collected from either the GRAnD database (Lehner et al., 2011) or from water provider websites. Information on alternative water sources (e.g., desalination) was obtained directly from individual water utility websites or other reports where available. Informal water supply mechanisms (e.g. water vendors) may be important components of the urban supply in some cities (Gandy, 2006), but were not represented in this study due to inadequate data availability.

3.2 Institutional Complexity

Institutional complexity was assessed as a function of 1) delivery capability 2) regulatory environment and 3) supply source portfolios. *Delivery capability* represents the functionality of the urban distribution system as measured by the degree of access provided, the continuity of water service, the extent to which connections are metered, and amount of unaccounted-for (non-revenue) water. Systems that only cover a portion of the urban population either spatially or temporally and are inefficient (e.g. low metering levels, high unaccounted-for water loss) are categorized as lacking the necessary complexity (e.g., authority, funds, and/or staff) required to adequately and efficiently distribute water. The *regulatory environment* includes the rules by which water supplies are managed, including urban water sharing strategies and laws or policies in place to actively manage surface and/or groundwater resources at either the state or national level. Large cities that participate in shared urban water management were classified as either utilizing urban-urban sharing strategies, where two or more large cities co-operatively manage sources of water (e.g. shared access to a reservoir), or urban-rural sharing strategies, where a large city receives water from a regional provider that also sources water to smaller communities or agricultural systems. It is assumed that the institutional regulatory environment becomes more complex when urban areas must co-manage resources or when rules or regulations dictate how water can be used or accessed (Allen et al., 1999; Bettencourt et al., 2007). The *supply source portfolio* reflects the increased management complexity associated with greater diversification, including multiple sources that may vary by distance or type. Here, it is assumed that cities with supplies outside of their jurisdictional control, or with more diverse source supply portfolios, utilize a more complex set of water management strategies to increase their water security. Data for assessing delivery capability and regulatory environments in African cities came from the International Benchmarking Network database (IBNET, 2015), the United Nations (2012), and additional supporting literature (Table S-2). Information for US cities was collected primarily from a state-level assessment by Flood (1990), the US Environmental Protection Agency Community Water Systems Survey (2002) and the American Water Works Association (2004).

Each of the three categories of institutional complexity was assessed using a set of four metrics (Table 1). Using a binary scoring system of 0 (absent) or 1 (present), an urban water supply Institutional Complexity Assessment (ICA) scale was developed as the sum of points scored across all twelve metrics. Higher ICA scores are assumed to be associated with the development of more complex institutions – more extensive provisioning using more sources in a more regulated environment. In this work, the relationship between ICA scores, urban

Table 1 The individual metrics that comprise the Institutional Complexity Assessment are based on three categories (delivery capability, supply source portfolio, and regulatory environment), each with four associated metrics. The percent of sampled US and African cities meeting each metric is indicated

Complexity Category	Assessment Metric	US Cities	African Cites
Delivery Capacity	Percent of non-revenue water (<10 %)	52 %	2 %
	Percent of connections metered (>50 %)	94 %	41 %
	Population with access to water (>50 %)	100 %	62 %
	Continuity of service (>12 h/day)	100 %	59 %
Supply Source	Uses captured (distant) sources	40 %	55 %
	Uses captured (distant) and local (near) sources	22 %	24 %
	Supplies come from more than one source	66 %	79 %
	Supplies come from more than one source type	38 %	67 %
Regulatory Complexity	Urban-urban strategies (e.g. co-manage urban source)	30 %	0 %
	Urban-rural strategies (e.g. regional water provider)	14 %	45 %
	Has mechanisms for groundwater management	60 %	47 %
	Has mechanisms for surface water management	78 %	62 %

water availability and income is evaluated. The individual metrics that comprise the ICA are also examined by water availability type. Urban per capita gross domestic product (GDP, in purchasing power parity in 2000) was obtained from the spatially-gridded GEcon database (Nordhaus et al., 2012), used here as a proxy for the financial capacity of a given urban area.

Note that data availability limits the ICA approach to providing an overview of the institutional mechanisms by which individual urban areas affect and are affected by water insecurity, and do not fully encompass all the legal and political nuances of urban water management. Further, the assumptions required to fill hydrologic data gaps (i.e. reservoir/lake allocations, environmental demand) can introduce error into availability estimates for a given city. However, the spectrum of hydrologic conditions and institutional complexity integrated in this assessment provide a much needed macroscopic view of the array of physical and socioeconomic challenges faced by urban water managers.

4 Results and Discussion

4.1 Urban Water Availability

The typology of Fig. 1 was evaluated for the 108 urban areas by plotting total water availability (Q_T) in liters per capita daily (lpcd) as a function of locally available water (Q_L) (Fig. 2). An exponential regression was applied to the log-transformed water availability estimates. The divergence of the regression from the 1:1 line increased as Q_L decreased, indicating that the proportion of total water available represented by captured water increased in naturally water scarce urban areas and that naturally water-rich urban areas with Q_L> 10,000 lpcd were unlikely to access captured sources. Based on the regression for the entire sample, cities with no locally available water are predicted to capture an average of approximately 230 lpcd. Applying a regression by region showed that cities with no locally available water would seek to capture 640 lpcd in the US and 210 lpcd in Africa. The latter value sits near a minimum

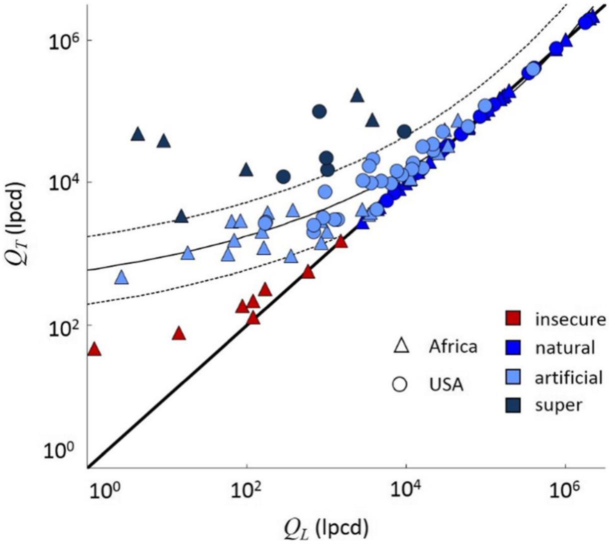

Fig. 2 Total urban water availability (Q_T) is the sum of the local (Q_L) and captured (Q_C) sources. The thin solid line represents an exponential regression with dotted lines mapping upper and lower thresholds of exceptional urban water availability. These thresholds were used to map the measured data from 108 cities in Africa and the US onto the urban availability typology of Fig. 1: natural (*blue*), artificial (*light blue*) and super (*dark blue*) abundance. Cities below the lower threshold were categorized as having physical or institutional water insecurity (*red*), with insufficient strategies to deal with water stress

(150 lpcd) proposed by Gleick (1996) for urban water needs. The difference between the two regions partially reflects greater aridity for the sampled cities in Africa (there are four times as many African cities with local water availability <230 lpcd than US cities) but may also indirectly account for cultural differences in water use (e.g. landscape irrigation).

The standard error of the predicted availability was used to set reasonable upper ($Q_{T,u}$) and lower boundaries ($Q_{T,l}$) demarcating instances of exceptional urban water availability. As shown on Fig. 2, cities above (below) the upper (lower) boundary significantly exceed (fall short of) the annual availability predicted here. Using $Q_{T,u}$ and $Q_{T,l}$ as quantitative thresholds, cities were assigned a category in the water availability typology (grouped by color in Fig. 2). Cities with a *natural abundance* of water (e.g., Kampala, New Orleans) are able to secure a mean annual supply from local sources that is adequate for meeting urban needs ($Q_T = Q_L$ and $Q_T > Q_{T,l}$). This is the second most common typology representing 38 % and 36 % of African and US cities, respectively.

Naturally drier cities that capture substantial volumes of water to supplement or use in place of local sources rely on extended systems of infrastructure to obtain water (*artificial abundance*, $Q_T > Q_L$ and $Q_T > Q_{T,l}$). This represents the most common typology, accounting for 38 % of African cities and 54 % of US cities. To capture additional water, most cities seek access to one or more surface or groundwater reservoirs, although this approach has geographical and financial limitations.

Cities that have been able to capture water from sources well beyond the requirements of a typical city in this sample have found *super abundance* ($Q_T > Q_{T,u}$). Similar to cities with artificial abundance, these areas have extended their supply portfolio to import water from outside their UAB. Yet, the supply available from these sources is substantial, situating these cities well above the upper water availability boundary. In this category, 10 % of sampled African cities and 10 % of sampled US cities face no imminent water availability issues because of these advantageously large sources.

Finally, cities lying below the lower water availability boundary ($Q_T < Q_{T,l}$) are categorized as lacking either the natural abundance or the ability to secure enough additional water through infrastructure, and therefore suffer from *water insecurity.* These eight cities are all African and are clustered near the lower end the local water availability spectrum.

In this analysis, typologies are demarcated according to mean water availability. However, water supply variability, such as from droughts, may shift cities from one typology to another. Further work that accounts for temporal variability in urban water supplies would help identify which cities may be susceptible to this type of typological shift.

4.2 Institutional Complexity

The relationship between ICA scores and local water availability is evaluated in Fig. 3. Institutional complexity was found to increase as locally available water decreased in both African and US cities, reflected in the negative correlation between mean local availability and institutional complexity ($R_{adj}^2 = 0.55$, p-value =0.008 and $R_{adj}^2 = 0.31$, p-value =0.056 for US and African cities, respectively).

US cities exhibited a higher mean institutional complexity score (6.9 ± 2.2) than African cities (5.4 ± 2.4), with only US cities displaying the highest levels of complexity (ICA > 10), and no US cities exhibiting the lowest levels of complexity (ICA < 3) (Fig. 4a). Figure 4b shows institutional complexity by type of availability. Cities with natural abundance are the dominant availability types for ICA < 6 (Fig. 4b). These cities occur throughout Sub-Saharan Africa and the eastern half of the US. African cities with natural abundance tend to be located around large-volume waterbodies (e.g. Kampala) (Fig. 5a). In the US, cities with natural abundance sit atop large groundwater resources (e.g. Jacksonville) or are adjacent to major rivers (e.g. Memphis) or the Great Lakes (e.g. Buffalo) (Fig. 5b). With ample local water, cities of this typology have had to devote relatively little resources towards capturing additional water and thus have significantly lower mean ICA scores (4.8 ± 2.0) than those with artificial or super abundance (Fig. 6a).

In contrast, artificial abundance dominates for ICA > 6 (Fig. 4b). Cities with artificial or super abundance actively find additional water sources to meet urban demands and in doing so reflect higher levels of institutional complexity, with mean ICA scores of 7.2 ± 2.2 and 7.5 ± 1.8, respectively (Fig. 6a). Artificial abundance appears in African cities along the

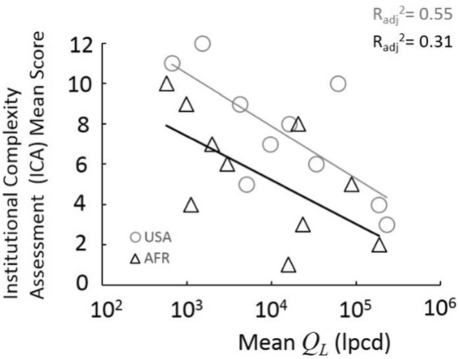

Fig. 3 Cities with lower locally water availability, Q_L, manifest higher levels of institutional complexity, represented as a function of water provision capability, supply infrastructure, and the level of regulatory activity. While cities in both the US (*grey circles*) and Africa (*black triangles*) exhibit similar negative relationships between water availability and institutional complexity, in most cases US cities have access to at least an order of magnitude more water than African cities with the same ICA score

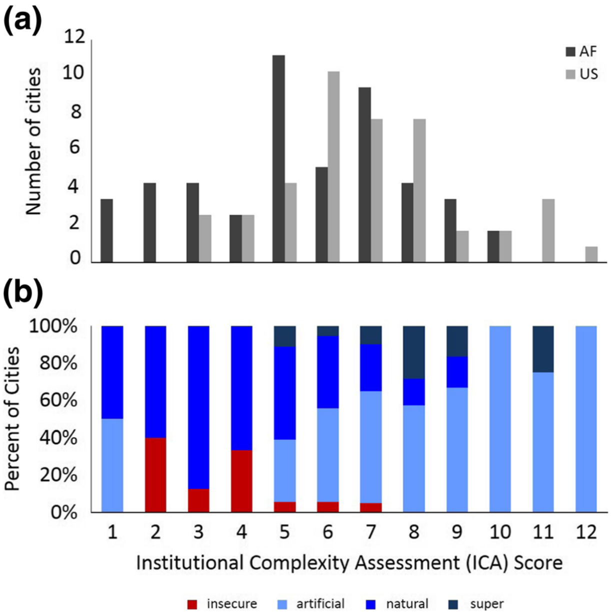

Fig. 4 Institutional complexity by (**a**) region, where ICA scores are significantly lower (Welch t-test, $p < 0.005$) in African versus US cities. When examined by (**b**) availability type, natural abundance dominates at lower levels of institutional complexity, and artificial abundance is most prevalent at greater levels of institutional complexity

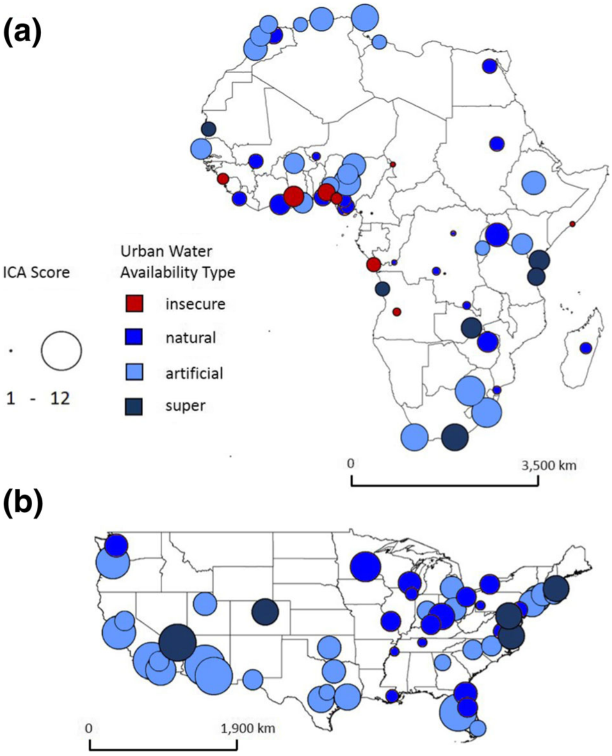

Fig. 5 Urban water availability type and institutional complexity for cities in (**a**) Africa and (**b**) the US. The size of the city marker represents the level of institutional complexity measured

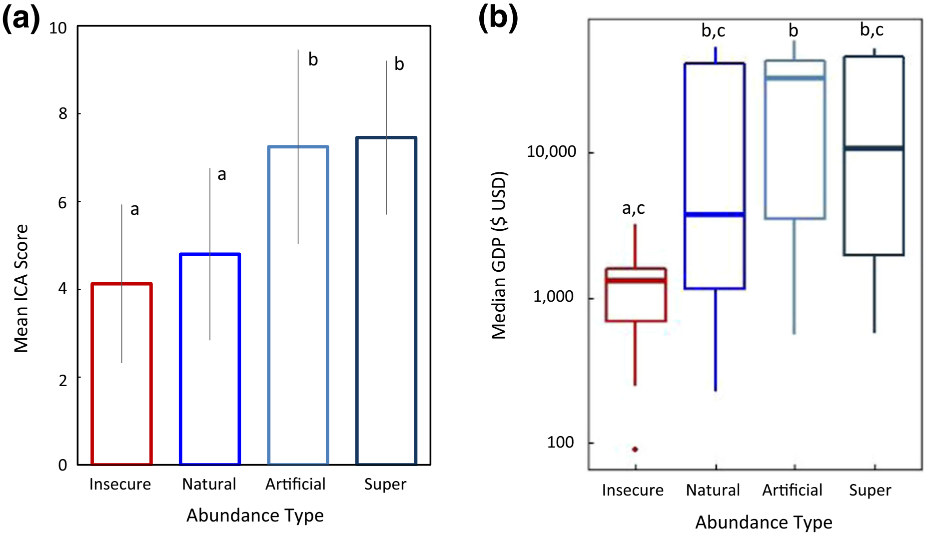

Fig. 6 Relationships between (**a**) mean institutional complexity assessment (ICA) scores and (**b**) median urban GDP by urban water abundance type. Vertical lines represent the (**a**) standard deviation and (**b**) interquartile range for each group. Lettered superscripts denote statistically significant differences

northern coastlines that utilize desalination (e.g. Algiers, Tunis, Oran), and wherever cities create or extend infrastructure to capture water (Fig. 5a). In the US, artificial abundance dominates in the western half of the country (e.g. Tucson, Los Angeles, Dallas) where groundwater use and large reservoirs designed for over-year (v.s. seasonal) storage are more common (Fig. 5b). Much of the super abundance found in the US is concentrated in the eastern half of the country, where substantial hydraulic infrastructure projects in relatively water-rich areas have boosted water supply availability well beyond other cities in this study.

The mean ICA score for the water insecure cities (4.1 ± 1.8) was the lowest of the four typologies and was statistically different from scores for artificial and super abundance ($p < 0.001$) – but not natural abundance (Fig. 6a). This suggests that while simpler institutional frameworks may work reasonably well for cities with ample water supplies, low institutional complexity may be a limiting factor constraining urban water availability in areas of natural water scarcity. For instance, urban water availability in Muqdisho and Huambo has declined as internal conflict has caused urban supply networks to collapse. Without a water supply system to collect and distribute sufficient water sources, residents have had to turn to untreated shallow groundwater and/or water vendors for supplies. Ibadan, Kumasi, Pointe Noire and Conakry all have limited local water availability and thus utilize reservoirs or river imports as primary sources. However, the estimated volume of water captured from these sources is low, indicating that the water supply management is not keeping up with demand, even for cities like Ibadan and Kumasi, both of which have relatively high ICA scores (7). In contrast, according to estimated natural water availability, Benin City and N'Djamena have the smallest water deficit, but appear to lack adequate supply systems to bring these cities to artificial abundance. Finally, it is important to remember that while water quantity issues are a major challenge, many cities also suffer from poor water quality, exacerbated by poor urban sanitation, which only adds to the issues that must be addressed as these cities adapt to the changing demands of the urban population.

4.3 Drivers of Water Insecurity

This section examines the relationship between urban GDP, water availability and institutional complexity, and also assesses the extent to which individual delivery, supply and regulatory metrics play a role in how water is managed.

4.3.1 Urban GDP

The World Bank (2014) income classification system was used to group urban areas into three categories: high income (per capita GDP > \$12,275), low-income (per capita GDP < \$1005), and mid-level income between these boundaries. Median urban GDP in the sampled US cities (\$42,200) is an order of magnitude larger than that of the sampled African cities (\$1500). The majority of African cities are classified as either low (33 %) or mid-level income cities (60 %), the remaining 7 % are high-income cities. In contrast, US cities are all in the high income category.

Median GDPs were statistically different for cities with artificial and insecure abundance (Fig. 6b). In addition, cities with water insecurity have median GDPs close to being statistically different from natural and super abundant cities, but fail to be significant under the Bonferroni correction for multiple comparisons (critical $p < 0.0083$). While not statistically significantly different, cities with natural and super abundance have median GDPs 2.8 and 7.9 times greater than those with insecure abundance, respectively. This suggests water insecurity is associated with both low GDP and low ICA scores. A positive relationship ($R^2 = 0.45$) was found between the log median GDP and ICA score for the sampled African cities, while no relation was found for US cities.

4.3.2 Individual ICA Metrics

The individual metrics that comprise the ICA are reported by region in Table 1. Delivery capacity was substantially higher for the sampled US cities than the African cities for each of the four metrics assessed. All US cities supplied >50 % of their urban population > 12 h of service per day. In contrast, approximately 60 % of African cities met this capacity. Nearly all US cities (94 %), but less than half of African cities (41 %), were metering water delivery to urban residents to enhance cost recovery and encourage demand management. The delivery metric met by the fewest cities was the requirement that non-revenue water be no more than 10 % of deliveries. Even in the US this is a high standard, with just over half of the US cities (52 %) sampled meeting this criterion, often owing to leaky, aging water infrastructure. In African cities, high levels of unaccounted-for water are common and can occur for many reasons including aging infrastructure and informal connections to the delivery system.

African cities scored higher on supply source complexity than US cities, with more captured water and a greater number and variety of sources (Table 1). Collectively, nearly half (45 %) of all sampled cities with low Q_L (<10,000 lpcd) had to extend beyond the UAB to secure water, utilizing 3.0 (interquartile range, IQR = 4.0) sources to meet urban demands, and reaching 24.4 (IQR = 46.24) km to reach these bodies of water. Note that for these skewed distributions, median and IQR is reported rather than mean and standard deviation. In contrast, only 3 % of all sampled cities with high Q_L (>10,000 lpcd) use water outside of their UAB. These cities access 4.0 (IQR = 1.0) sources over much shorter distances (4.3 km, IQR = 6.7) than analogous cities with low Q_L (<10,000 lpcd), suggesting arid conditions are associated with a higher degree of supply source complexity. For example, arid-region Algiers and Tunis use a combination of surface and/or groundwater and desalination to meet urban demands, a strategy that takes advantage of the different benefits and sensitivities of each type of source. Cities that met all four criteria in the supply source category (e.g. Durban, Nairobi, Phoenix-Mesa, Los Angeles-Long Beach-Santa Ana) maintain water collection systems that control distant and varied supply portfolios.

Regulatory complexity was difficult to quantify because of relatively sparse data on urban-level source sharing, regional water supply systems, and in particular, rules for groundwater and surface water management. The best data on groundwater and surface water management available for this study occurred at the state-level for US cities and the national level for African cities. A larger portion of US cities use urban-urban sharing strategies, and have rules in place for both groundwater and surface water management (Table 1). In contrast, more African cities use urban-rural sharing strategies, where regional water providers supply water to a single large city and many smaller towns. The only city in the sample that met all four regulatory complexity criteria, Phoenix-Mesa, manages supplies under state-defined ground and surface water management rules, purchases water from a regional water supplier, and also shares one or more sources with another large city.

5 Conclusions

Cities represent complex systems where the water needed for growth and development depends on both the local hydrologic conditions and the physical and institutional mechanisms by which water resources are procured and managed. Many studies have contributed to better understanding of either the physical hydrologic landscape or the socioeconomic institutions that guide water management, but work that utilizes both types of knowledge is critical for supporting an equitable, sustainable future. This work targets this gap by providing a quantitative assessment of the relationship between urban water availability and institutional complexity for large cities in Africa and the US.

The results presented here show that cities are increasingly likely to seek captured water when local availability falls below 10,000 lpcd. For these cities with relatively low locally available water, managers must find a way to capture distant sources of water to move from a state of insecurity to one of artificial abundance. This strategy of artificial abundance is the most common of the cities studied here, representing 45 % of the sample, however the investments in institutional complexity required for capturing additional water are significant. Cities with artificial abundance have significantly higher ICA scores (7.2 ± 2.2) than those with natural abundance (4.8 ± 2.0) or water insecurity (4.1 ± 1.8). In addition, while urban GDP alone is not a strong predictor of water security, evidence suggests that low GDP may be a constraint on developing institutional complexity. Given these findings, the greater investments required to reach artificial abundance may act as a barrier to development in cities that are rapidly growing and/or have limited resources to begin with. However, urban areas with a long history of artificial abundance may also find their past infrastructure investments and management techniques are inadequate in the face of fully allocated resources. The results provided here offer a foundation for future work on urban water sustainability and highlight the need for more rigorous benchmarking and policy-relevant science on the deeply intertwined connection between urban water security and the greater human-natural landscape.

Acknowledgements This research was supported in part by USDA National Institute of Food and Agriculture Hatch projects FLA-SWS-005461, the Adaptive Management of Water, Wetlands and Watersheds IGERT program at the University of Florida, the State of Washington Water Research Center and the Center for Environmental Research, Education and Outreach at Washington State University.

References

AIDC (2013) Africa Development Bank Group- National and Operator Databases. http://www.infrastructureafrica.org/tools. Accessed 9 May 2013

Allen TF, Tainter JA, Hoekstra TW (1999) Supply-side sustainability. Syst Res Behav Sci 16:403–427

AWWA (2004) 2004 Water & wastewater rate survey. American Water Works Association, Denver

Bettencourt L, Lobo J, Helbing D, Kühnert C, West GB (2007) Growth, innovation, scaling, and the pace of life in cities. Proc Natl Acad Sci 104:7301

Blomquist W, Heikkila T, Schlager E (2004) Building the agenda for institutional research in water resource management. J Am Water Resour Assoc 40:925–936

Brown RR, Farrelly MA, et al. (2009) Delivering sustainable urban water management: a review of the hurdles we face. Water Sci Technol 59:839

CIESIN (2004) Global Rural–Urban Mapping Project (GRUMP): Urban/Rural Extents. Center for International Earth Science Information Network (CIESIN), Columbia University, International Food Polilcy Research Institute (IPFRI), World Bank and Centro Internacional de Agricultura Tropical (CIAT), Palisades, NY

EPA (2002) 2000 EPA community water system survey. Environmental Protection Agency, Washington D.C

Estache A, Kouassi E (2002) Sector Organization, Governance, and the Inefficiency of African Water Utilities. World Bank Policy Research Working Paper. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=636253. Accessed 4 Apr 2016

Falkenmark M (1990) Rapid population growth and water scarcity: the predicament of Tomorrow's Africa. Popul Dev Rev 16:81–94

Fekete BM, Vörösmarty CJ, Grabs W (2002) High-resolution fields of global runoff combining Observed River discharge and simulated water balances. Glob Biogeochem Cycles 16:15–11

Flood PK (1990) "Water Rights" of the fifty states and territories. In: Wright KR (ed) Water right of the fifty states and territories. American Water Works Association, Denver

Gandy M (2006) Water, Sanitation and the Modern City. Occasional Paper, United Nations Development Programme

Gleick PH (1996) Basic water requirements for human activities: meeting basic needs. Water Int 21:83–92

Graedel TE, Klee RJ (2002) Getting Serious about sustainability. Environ Sci Technol 36:523–529

Grey, D. and C.W. Sadoff, 2007. Sink or swim? Water security for growth and development. Water Policy 9:545.

IBNET (2015) The International Benchmarking Network for Water and Sanitation Utilities (IBNET) Database. https://www.ib-net.org/

Jacobsen M, Webster M, Vairavamoorthy K (2012) The future of water in African cities: why waste water? World Bank Publications, Washington D.C

Jenerette GD, Larsen L (2006) A global perspective on changing sustainable urban water supplies. Glob Planet Chang 50:202–211

Kemper KE (2001) The role of institutional arrangements for more efficient water resources use and allocation. Water Sci Technol 43:111–117

Kiparsky M, Sedlak DL, Thompson BH, Truffer B (2013) The innovation deficit in urban water: the need for an integrated perspective on institutions, organizations, and technology. Environ Eng Sci 30:395–408

Lehner B, Liermann CR, Revenga C, Vörösmarty C, Fekete B, Crouzet P, Döll P, Endejan M, Frenken K, Magome J, Nilsson C, Robertson JC, Rödel R, Sindorf N, Wisser D (2011) High-resolution mapping of the World's reservoirs and dams for Sustainable River-flow management. Front Ecol Environ 9:494–502

Lundqvist J, Tortajada C, Varis O, Biswas A (2005) Water Management in Megacities. AMBIO. A Journal of the Human Environment 34:267–268

MacDonald AM, Bonsor HC, Dochartaigh BÉÓ, Taylor RG (2012) Quantitative maps of groundwater resources in Africa. Environ Res Lett 7:24009

McDonald RI, Douglas I, Revenga C, Hale R, Grimm N, Grönwall J, Fekete B (2011) Global urban growth and the geography of water availability, quality, and delivery. Ambio 40:437–446

McDonald RI, Weber K, Padowski J, Flörke M, Schneider C, Green PA, Gleeson T, Eckman S, Lehner B, Balk D, Boucher T, Grill G, Montgomery M (2014) Water on an urban planet: urbanization and the reach of urban water infrastructure. Glob Environ Chang 27:96–105

Meigh JR, McKenzie AA, Sene KJ (1999) A grid-based approach to water scarcity estimates for eastern and southern Africa. Water Resour Manag 13:85–115

Meinzen-Dick R (2007) Beyond panaceas in water institutions. Proc Natl Acad Sci 104:15200–15205

Muller M (2007) Adapting to climate change water Management for Urban Resilience. Environ Urban 19:99–113

Nafi A, Tcheng J, Beau P (2015) Comprehensive methodology for overall performance assessment of water utilities. Water Resour Manag 29:5429–5450

Nordhaus W, Azam Q, Corderi D, Hood K, Victor N, Mohammed M, Miltner A, Weiss J (2012) The G-econ database on gridded output. Yale University, New Haven

Padowski JC, Jawitz JW (2012) Water availability and vulnerability of 225 large cities in the United States. Water Resour Res 48. doi:10.1029/2012WR012335

Pierce JC, Budd WW, Jr NPL (2011) Resilience and sustainability in US urban areas. Environ Polit 20:566–584

Proença de Oliveria R, Saldanha Matos J, Monteiro AJ (2015) Managing the urban water cycle in a changing environment. Water utility. Journal 9:3–12

Saleth RM, Dinar A (2004) The institutional economics of water. MPG Books Ltd., Cheltenham

Schneider F, Bonriposi M, Graefe O, Herweg K, Homewood C, Huss M, Kauzlaric M, Liniger H, Rey E, Reynard E, Rist S, Schädler B, Weingartner R (2015) Assessing the sustainability of water governance systems: the sustainability wheel. J Environ Plan Manag 58:1577–1600

Scholz, JT and Stiftel B, (2005) Adaptive governance and water conflict: new institutions for collaborative planning. Resources for the Future, Washington, D.C

Showers KB (2002) Water scarcity and urban Africa: an overview of urban–rural water linkages. World Dev 30: 621–648

United Nations (2012) Status report on the application of integrated approaches to water resources management. UN Water Report, UN-Water for the Rio + 20 Summit

United Nations (2014) Population division: world urbanization prospects, the 2014 revision. Department of Economic and Social Affairs, New York

USCB (2009) Metropolitan and Micropolitan Statistical Areas. Tables and Datasets. http://www.census.gov/popest/data/metro/totals/2009/index.html.

van Leeuwen CJ, Frijns J, van Wezel A, van de Ven FHM (2012) City blueprints: 24 indicators to assess the sustainability of the urban water cycle. Water Resour Manag 26:2177–2197

Vörösmarty CJ, Douglas EM, Green PA, Revenga C (2005) Geospatial indicators of emerging water stress: an application to Africa. Ambio 34(3):230–236

Weiskel, P.K., R.M. Vogel, P.A. Steeves, P.J. Zarriello, L.A. DeSimone, and K.G.R. III, 2007. Water use regimes: characterizing direct human interaction with hydrologic systems. Water Resour Res 43:W04402.

World Bank (2014) World Bank GNI per Capita Operational Guidelines & Analytical Classifications. http://siteresources.worldbank.org/DATASTATISTICS/Resources/OGHIST.xls.