Water availability and vulnerability of 225 large cities in the United States

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[1] This study presents a quantitative national assessment of urban water availability and vulnerability for 225 U.S. cities with population greater than 100,000. Here, the urban assessments account for not only renewable water flows, but also the extracted, imported, and stored water that urban systems access through constructed infrastructure. These sources represent important hydraulic components of the urban water supply, yet are typically excluded from water scarcity assessments. Results from this hydraulic-based assessment were compared to those obtained using a more conventional method that estimates scarcity solely based on local renewable flows. The inclusion of hydraulic components increased the mean availability to cities, leading to a significantly lower portion of the total U.S. population considered “at risk” for water scarcity (17%) than that obtained from the runoff method (47%). Water vulnerability was determined based on low-flow conditions, and smaller differences were found for this metric between at-risk populations using the runoff (66%) and hydraulic-based (54%) methods. The large increase in the susceptible population between the scarcity measures evaluated using the hydraulic method may better reconcile the seeming contradiction in the United States between perceptions of natural water abundance and widespread water scarcity. Additionally, urban vulnerability measures developed here were validated using a media text analysis. Vulnerability assessments that included hydraulic components were found to correlate with the frequency of urban water scarcity reports in the popular press while runoff-based measures showed no significant correlation, suggesting that hydraulic-based assessments provide better context for understanding the nature and severity of urban water scarcity issues.


1. Introduction

[2] Ensuring that cities have an adequate supply of water is increasingly important as human populations continue to concentrate in urban areas. Globally, urban populations have increased from 30% in 1950 to over 50% as of 2010 [United Nations (UN), 2012]. In the United States, a similar trend has been recorded, as more than 80% of the U.S. population now live in urban areas, compared to 64% in 1950 [UN, 2012]. Water demands in the U.S. public supply sector have correspondingly increased steadily with population growth, more than tripling since 1950 [Huston et al., 2005]. Rapidly growing urban demands are straining local and regional water supplies, however, and concerns over urban water scarcity in the United States are becoming more prominent [Levin et al., 2002]. Recent reports of water shortages, such as those in Atlanta, GA, in 2008, and San Francisco, CA, in 2006–2007 [Dorfman et al., 2010], reflect deeper concerns about the impacts of climate change, population growth, and environmental regulation on water supplies [Ginley and Ralston, 2010; Means et al., 2005]. Water quality issues also represent a looming concern for urban areas. Contamination due to leaking sanitation infrastructure, nonpoint source anthropogenic pollution, and xenobiotics all decrease the volume of usable water available for urban water systems [Schirmer et al., 2011]. Anxiety over urban water scarcity issues was formally highlighted in a survey by the American Water Works Association, which revealed that the primary issue of concern for water managers was source water availability, i.e., maintenance of adequate volumes of treatable water available for consumption [Runge and Mann, 2008].

[3] Although some control over utility operations occurs at the federal and state levels, local utilities are largely responsible for creating, evaluating, and monitoring their own performance [Baumann et al., 1998]. The flexibility associated with a decentralized regulatory policy has been advantageous in that it has allowed utilities to develop unique management solutions, such as the use of storages and water transfers/imports to mitigate the natural variability of urban supplies. In many cases, these solutions are
critical for alleviating the effects of short-term deficits in water availability (drought); however, continual reliance on these types of sources to compensate for long-term (arid) deficits can lead to substantial reductions in total storage and user conflicts.

[4] Making sustainable water management decisions in an increasingly uncertain environment requires an improved understanding of water availability and vulnerability. Water availability assessments should provide clear data regarding how much water is available for use on an average annual basis, and vulnerability assessments are necessary for evaluating the ability of available water sources to meet needs under conditions of water stress. By understanding how water availability and vulnerability issues affect, and are affected by urban water systems, water-related conflicts related to both environmental and human needs can better be addressed without overinvesting or undersupplying [National Research Council (NRC), 2002].

2. Water Scarcity Assessments

[5] It has long been known that urban areas are locations of high productivity whose success depends heavily on their ability to procure natural resources [Harris and Ullman, 1945]. Historically, these areas have been particularly proficient at securing water supplies by constructing infrastructure to extract, import, and store water for urban needs [Melosi, 2000]. These anthropogenic modifications make urban water scarcity assessments difficult, however, since the assumptions normally used to simplify hydrologic analyses depend on conditions that exclude important components of urban water supply. One such difficulty arises from the fact that political boundaries rarely correspond with hydrologic ones [Blomquist and Schlager, 2005]. Many urban areas import and/or share water from other basins, occasionally across great distances and as such, traditional hydrologic boundaries are no longer useful for defining the system extent. Additionally, the assumption of equilibrium, in which a system experiences no net change in storage over time, is often used in hydrologic assessments to avoid the difficult task of quantifying the total volume of water available. However, nearly all urban areas rely on some form of storage, either below or above ground, as part of their supply portfolio. Given the heavy urban dependence on storage, assessments that focus exclusively on system inflows and outflows thus inherently exclude a critical component of urban water systems.

[6] While water scarcity has been studied on many scales and with a wide range of methodologies, there has been no comprehensive national assessment of urban water scarcity in the United States. Global assessments of water scarcity indices [Sekler et al., 1998; Shiklomanov and Rodda, 2003; Sullivan et al., 2003] and spatially distributed global water balance models [Alcamo et al., 2007; McDonald et al., 2011; Vörösmarty et al., 2000] have added much to our understanding of water resources and management, but their resolutions are too coarse to accurately capture the hydraulic components of urban water management. National-scale assessments have been conducted at finer resolutions based on county [Roy et al., 2005] or local groundwater/surface water basin boundaries [Anderson and Woosley Jr., 2005; Brown et al., 2008; Hurd et al., 1999; Lane et al., 1999; Sun et al., 2008]. These studies tend to rely upon historical river flow records or the estimation of mean annual runoff from other widely available data such as the difference between precipitation and evapotranspiration. However, like global analyses, these more refined assessments do not include necessary information for comprehensively evaluating urban water issues.

[7] Local studies that focus on water scarcity in cities or urban watersheds [Borchert, 1954; Claessens et al., 2006; DeWalle et al., 2000; Hagen et al., 2005; Jenerette et al., 2006a, 2006b; Sloto and Buxton, 2006; Ward et al., 2006] do include the types of information relevant for urban analyses; however, the complexity of the data required (both spatially and temporally) and variability in the methodologies used tend to preclude synthesis across studies. Finally, urban utilities frequently and independently assess water availability and vulnerability as part of their planning processes [Viessman and Feather, 2006]. However, with no standardized methodology, the depth and breadth of municipal-scale assessments can vary widely between utilities, confounding intercomparisons. Outside of contacting utilities on an individual basis, there are few other outlets from which information related to urban water provision can be indirectly obtained. This variability in the quality and availability of urban water information is in part the product of a void in national water policy [Stakhiv, 2003].

[8] While there has been no federal synthesis of information regarding urban water provision at the national level, over the past 30 years many federal initiatives, primarily under the direction of the U.S. Geological Survey (USGS), have been performed to characterize water resources at the national scale. The last executive-ordered comprehensive overview of national water resources was performed in 1978 by the U.S. National Resources Council, providing a general overview of water availability, withdrawals and use, and contextualized hydrologic concerns and management solutions (e.g., flooding, pollution, and erosion/sedimentation) by watershed. Despite growing concerns over climate change and significant changes in water use and population growth and redistribution, a comparable national assessment was not initiated until 2009, when the U.S. Congress promulgated the Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act. Currently in progress, this act authorized the USGS to create and implement a new comprehensive national assessment of water availability and use [Konrad, 2010]. However, it is not clear whether an exhaustive urban assessment will be included or how available storage, imports, and transfers will be incorporated into the methodology.

[9] This work seeks to formulate a quantitative assessment of urban water scarcity that accounts for both the hydrogeography and the infrastructural adaptations used by urban areas. The objective of this study was to produce a national assessment of water availability that examined both traditional measures of availability and how the role of urban hydraulic components (i.e., storages and imports) could be used to develop a better understanding of water vulnerability in U.S. urban areas. Specifically, this work assessed (1) the extent to which water scarcity measured using a hydraulic-based approach differs from results derived from methods using only renewable flow information, (2) the relative contribution of hydraulic components...
to the overall urban supply portfolio, (3) the sensitivity of estimated water availability-related risk to important hydraulic parameters, (4) the degree to which low-flow variability may affect the vulnerability of urban systems, and (5) how well the presented vulnerability assessments compared to press accounts of urban water scarcity. While this study is meant to be a comprehensive, national hydrologic assessment for urban areas, it does not examine the impact of other important controls on urban water sustainability, such as the institutional and legal parameters within which urban water management must operate. These frameworks can have a substantial impact on local and regional water accessibility; however, an analysis of urban scarcity issues from this perspective is beyond the scope of this paper.

Water availability and vulnerability assessments were performed for all major urban areas in the conterminous United States with populations greater than 100,000 that had sufficient data available \( (n = 225) \). Information on local hydrology, hydraulic adaptations, and water usage (Figure 1) were collected from publicly accessible databases (Table 1) and used to estimate the mean annual volume of water available for each urban area. These water availability assessments were compared to estimates from a more commonly used runoff-based approach in which only local renewable sources are considered. Vulnerability was determined using the decrease in source water inflows under stressed, or low-flow, conditions. The water vulnerability estimates produced using this method were compared to a media text analysis (MTA), where water vulnerability was measured as a function of local and national media attention on urban water stress. The MTA served as an independent, qualitative proxy of vulnerability. Based on this uniform, spatially explicit, national analysis of water availability and vulnerability for the largest cities in the United States, comprehensive assessments of “at-risk” populations were identified at the local and national levels.

3. Methodology

3.1. Water Availability and Vulnerability

The U.S. urban population is serviced almost exclusively by urban water utilities, thus making the water utility distribution area an appropriate scale for studying urban water scarcity issues. Regrettably, pertinent information regarding utility distribution, such as service population size, and areal extent, in particular, are often not readily available for many utilities. Potential substitutes for this type of information are the boundaries defined by the U.S. Census Bureau (USCB) to delineate areas of lower and higher population density. Three urban delineations were deemed potentially appropriate for this study: the city (U.S. Census Bureau (USCB), Incorporated places population, 2000–2009, Population Estimates—City and town totals: Vintage 2009, 2009a, http://www.census.gov/popest/data/cities/totals/2009/files/SUB-EST2009-IP.csv), urban area (USCB, Urban area populations, 2000, US Census Bureau Geography, 2000b, http://www.census.gov/geo/www/ua/ua2k.txt) and metropolitan statistical area (MSA) (USCB,

Figure 1. Hydrologic data for water flows and storages were collected from the publicly available databases listed in Table 1 and were compiled to estimate the water availability for each urban area (yellow). The relative magnitude of the local runoff and aquifer recharge is indicated by darker blue (higher) and lighter blue (lower) gradations.
Metropolitan and micropolitan statistical areas, Tables and datasets, 2009b, http://www.census.gov/popest/data/metro/totals/2009/index.html). Since information regarding utility population service size is more common than data regarding areal extent, service population data were used to identify the urban delineation that best represents the urban utility, wherein the populations of each of the three urban delineations were compared to the service population size of 100 major urban utilities (Figure 2). MSAs and urban areas were found to overestimate utility service population size by 82% ($R^2 = 0.69$) and 47% ($R^2 = 0.76$), respectively, whereas the city scale underestimated utility service population size by 49% ($R^2 = 0.70$). Based on the strength of the correlations and availability of data, the urban area scale was selected as the substitute for the total urban utility service population and areal extent.

Urban area information was collected from the U.S. USCB’s “urbanized areas” data set in the form of polygon features delineating the boundary of each urban area (USCB, Census 2000 urbanized areas cartographic boundary files—U.S. Census Bureau, 2000a, http://www.census.gov/geo/www/cob/ua2000.html). The urban areas used in this study are a subset of this data set including only those areas with populations $\geq 100,000$ ($n = 255$) and represent

<table>
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<th>Data Type</th>
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<tr>
<td>Urban water demand</td>
<td>Kenny et al. [2009]</td>
<td>Individual Consumer Confidence Reports</td>
</tr>
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$^a$USGS, US Geological Survey; NID, National Inventory of Dams; USCB, US Census Bureau; NHD, National Hydrography Database.

Figure 2. Relationships between three urban delineations and utility service population. Since many urban utilities do not make service population or areal extent information publicly available, a linear regression was used to determine the most appropriate substitute urban delineation. The urban area delineation provided the closest fit and was used in this study to represent urban water service populations and areal extents.
the particular spatial location, extent, and population size of each sample selected. In this analysis, urban area boundaries (UABs) were simplified by including a smoothing 5 km buffer around the perimeter of each and all subsequent references to the UAB include this 5 km buffer.

While population and areal information were considered substitutable, information regarding urban source water supplies can only be collected from individual water utilities. Unlike utility service extent, information about urban water sources must be made available to utility customers as mandated by the 1998 Consumer Confidence Report Rule under the Safe Drinking Water Act. Therefore, all primary urban utilities (n = 294) within urban areas were identified and their source supplies were collectively identified as those used by urban area residents.

Urban water resources included in this study were identified as either “natural” or “captured” based on their location relative to the urban area and whether they are obtained from a constructed source. Natural sources included all potentially usable, naturally occurring flows (i.e., rivers) or storages (i.e., lakes, groundwater) that intersected or bordered the UAB regardless of whether they are used for urban water supply. These sources collectively serve as a base estimate of the naturally available water in an urban area. Captured sources refer to any additional sources that have been acquired to supplement the urban area’s supply portfolio, including water from rivers and lakes outside of the UAB, water in reservoir storage, and pumped groundwater. Urban areas were excluded from the study when greater than 25% of the information regarding an urban area supply portfolio was missing from the available data sets. Adequate information for assessing water availability and vulnerability was accessible for 89% (n = 225) of the study areas.

Water availability was estimated using two methods. The first represented the commonly used “runoff” approach, where water availability (\( Q_R \) [L^3T^-1]) is equal to the volume of locally renewable water available to an urban area (equation (1)). “Hydraulically” available water (\( Q_H \) [L^3T^-1]) accounts for an urban area’s ability to construct infrastructure to extract, import, and store water, and therefore represented the volume of water available calculated as the sum of all natural and captured mean annual flow and storage volumes (equation (2)):

\[
Q_R = \mu_f + \mu_{a,n},
\]

\[
Q_H = \mu_{q,a} + \mu_{q,c} + \mu_{v,a} + \mu_{v,c} + \mu_{l,a} + \mu_{l,c} + \mu_{g,a} + \mu_{g,c},
\]

where \( \mu \) represents the mean annual flow or volume [L^3T^-1], and the subscripts indicate runoff (f), groundwater recharge (a), river discharge (q), reservoir storage (v), lake storage (l), and groundwater storage (g). Subscripts n and c indicate whether the term is natural or captured, respectively. Note that in equation (1), local runoff represents only locally generated flow rather than the cumulative volume generated from upstream basins. Equation (2) does not directly include local runoff, but rather assumes that these locally generated flows are embodied in the local discharge term. Specific methods used to quantify each of these components are discussed in the following sections.

To more clearly identify areas where low water availability may pose a potential risk to the urban population, a risk indicator was employed where scarcity occurs when the ratio of water demand (\( D \)) to water availability (\( Q \)) is above the threshold \( \gamma = 0.40 \) [Falkenmark, 1998; Vörösmarty et al., 2005]. Here, this scarcity ratio was rearranged to estimate the average minimum volume of available water needed by an urban area to avoid scarcity issues (\( Q' = D/0.40 \)). In this study, mean annual urban demand was found to be approximately 600 L/capita/day (Lpcd), resulting in \( Q' = 1500 \) Lpcd.

Whereas \( Q \) represents the average annual water availability, water vulnerability represents the variability in \( Q \) due to effects of seasonality, droughts, or prolonged overextraction. Normally, describing these fluctuations requires long-term historical data at subannual resolutions; however, this information is not widely available for all of the urban water sources under consideration. Instead, vulnerability was expressed as the susceptibility of urban supplies under low-flow, or severe drought-like, conditions. Low-flow risk (\( \alpha \)) was defined as the flow-weighted mean volume of all source water inflows using historical low-flow conditions for an urban area:

\[
\alpha = \frac{\sum (\mu_i \times \mu_P)}{Q^2},
\]

where \( \mu_i \) represents the mean annual inflow from each natural and captured source, and \( P_{10} \) is the low-flow volume available for each source when an inflow exceeded 90% of the time. Equation (3) was normalized by \( Q' \) to provide an explicit definition of water vulnerability relative to the mean minimum amount of water needed by an urban area. This volume-based definition eliminates the need for an arbitrarily defined limit of “vulnerable” versus “secure.” Urban locations facing threats from source variability are those with \( \alpha < 1 \), or have mean low flows that drop below the minimum water required to sustain an urban area.

3.2. Urban Supply and Demand

Water supply and demand information were obtained from water utilities serving each urban area. Since metropolitan areas can be served by many utilities, the data collection process was simplified such that only utilities serving primary municipalities were evaluated. Of the 255 urban areas under investigation, 30 were removed from the study for deficiencies in data related to utilities (7), reservoirs (8), lakes (3), and groundwater (12). From the remaining 225 urban areas, 271 principal municipalities were identified, for which data from 294 water utilities were found. For each of the utilities identified, the following data were collected: service area, service population size, total annual water provided, and main sources of supply. These data were compiled from local utility Web sites and U.S. Clean Water Act-mandated Water Quality/Consumer Confidence Reports. Each primary supply source listed by a utility (e.g., reservoir, river, aquifer, etc.) was identified in one of the hydrologic databases described later. Urban water demand (\( D \)) was calculated using an area-weighted average of the total public supply demand as reported by county in each urban area [Kenny et al., 2009].

3.3. Local Runoff

Local runoff has been estimated for all Hydrologic Unit Code cataloging units (HUC-8) in the coterminous
United States since 1901 by the U.S. Geological Survey (USGS waterwatch, Past flow and runoff, 2012, http://waterwatch.usgs.gov/new/index.php?id=romap3). These data represent the local hydrologic contribution from each HUC-8 area, rather than the cumulative volume from upstream basins. For this study, the mean annual local runoff was determined by computing the area-weighted mean runoff based on the portions of each HUC-8 region that overlapped an urban area.

3.4. Streamflow

Streamflow data were derived from two sources. Spatial data, which included the name, location, and stream order of over 10,000 rivers and streams, were obtained from the National Hydrography Dataset (U.S. Geological Survey—National hydrography dataset, 2008, http://nhd.usgs.gov/data.html). River discharge information, including mean annual discharge ($Q_a$), discharge exceedance probabilities ($P$), length of record, and variance in mean annual discharge were obtained from a USGS spatial database of 23,427 streamgages within the conterminous United States (USGS USGS water resources NSDI node, 2008a, http://water.usgs.gov/GIS/metadat/usgsgrid/XML/qlitesdd.xml). In cases where discharge information was unavailable, mean annual discharge was estimated from the associated NHD stream-order value (Chow, 1964).

In-stream environmental water demands were calculated from available streamflow by estimating a “minimum flow” required for maintaining a desired level of aquatic and riparian health. Minimum flow values were calculated based on the work by Smakhtin et al. (2004) who proposed a general set of guidelines for determining acceptable low-flow requirements based on the level of ecological disturbance of different management objectives. While it is recognized that the degree of management across river systems varies immensely, here an optimistic minimum flow value is set as the Q75, or flow that is exceeded 75% of the time. This low-flow characteristic corresponds to a system in which ecosystem functionality is relatively healthy and where there is slight-to-moderate hydrologic development within the basin (Smakhtin et al., 2004). Assuming this in-stream flow requirement, streamflow allocations for urban areas were estimated as:

$$P_{aq} = P_a - P_{aq}$$

where $\mu_a$ represents the total allowable mean annual measured discharge [L$^3$T$^{-1}$] and $\mu_{aq}$ is the mean minimum flow that is exceeded 75% of the time [L$^3$T$^{-1}$]. Vulnerability estimates were based on extreme low-flow conditions equal to the $P_{10}$ (Q90) exceedance frequency reported with the river discharge information.

It was assumed that urban areas do not utilize river sources that alone would be insufficient to meet combined minimum urban and environmental demands. Minimum urban demands were defined as the mean annual flow volume necessary to support a human population of at least 100,000 people using 600 lpcd (0.7 m$^3$ s$^{-1}$). Combining this value with the Q75 minimum environmental demands, a lower mean annual discharge cut-off value was determined to be 2.8 m$^3$ s$^{-1}$, or a stream order of $\leq$4 for bodies without discharge data. All streams and rivers below this cutoff were excluded from this study.

3.5. Reservoir Storages

Reservoir information, including dam and reservoir name, location, normal storage volume, source river name, drainage area, purpose, and ownership were obtained from the National Inventory of Dams (National Inventory of Dams, 2009, http://crunch.tec.army.mil/nidpublic/webpages/nid.cfm). In the 33 cases where a reservoir with the sole purpose of water supply is the source for only one urban area, the available water is equal to the reported normal storage volume ($\mu_v$) for that reservoir. In the 101 cases where a reservoir serves more than one purpose (e.g., water supply and hydropower generation) or urban area, conservative estimates of reservoir normal storage allocations were made by first equally dividing the total volume of storage between the assigned purposes, and second, equally dividing this modified storage volume between urban areas using the reservoir.

Information on stage variability for reservoir sources was not part of the NID database; therefore, variability in reservoir inflows served as a proxy for variability in reservoir normal storage in lieu of any other available information. Because discharge and exceedance frequencies were not consistently available for all of the rivers feeding each reservoir, information on reservoir inflows was instead estimated using a regional hydroclimatic regression model developed by Vogel et al. (1999b). This model was previously applied to successfully estimate the mean and variance of annual inflows to 5,392 U.S. reservoirs (Vogel et al., 1999a). Using the method developed by Vogel et al. (1999a), mean annual streamflow ($\mu_v$) and flow variance ($\sigma_v^2$) for individual rivers were estimated based on regional hydrologic and climatic information as follows:

$$\mu_v = \alpha A^a P_b T_c^d$$

$$\sigma_v^2 = \beta A^b P^c T^d$$

where $a$ through $i$ are empirical model parameters that are listed for each water region in Vogel et al. (1999b), $A$ is drainage area (km$^2$), $P$ is mean annual precipitation (mm yr$^{-1}$), and $T$ is mean annual temperature ($^\circ F \times 10$).

Vogel et al. (1999b) considered small basins, where it was assumed that river flows are unregulated and reservoirs operate independently of each other. Because these assumptions may not always be applicable in this study, the accuracy of equations (4) and (5) were compared to the available measured data from reservoirs with gaged river information ($n = 54$). The sample size used in this comparison was relatively small because six regions (3, 6, 8, 9, 13, and 16) had no measured discharge data available for reservoirs, while the remaining 13 regions only had data available for, on average, 11% of reservoirs in each basin. From these available data, the error between estimated and observed inflows for regions 1, 2, 4, 5, 14, and 17 were all found to be less than 40%; however, discrepancies between inflow measurements for reservoirs located in HUC regions 7, 10, 11, 12, 15, and 18 were substantially greater, with a mean error between estimated and observed inflows of 104%. Despite the limited subsample, this comparison suggests that the largest flow discrepancies occur in regions where the assumptions made by Vogel et al. (1999a) about unregulated flows and independently managed reservoirs may not hold true. Many large rivers in the southern and...
western half of the United States have multiple large dams along their reach, substantially impacting river flows and downstream reservoir operations. To account for these errors, a correction factor based on the average distance between the observed and measured data (Table 2) was applied to reservoirs in regions that had \( \geq 10\% \) gaged representation (regions 4, 5, 7, 10, 11, 12, and 14). Based on the assumption that daily flow distributions for most rivers in the United States can be reasonably approximated as log-normal [Vogel et al., 1999a], the adjusted mean annual flow and flow variance were then used to quantify each source river’s probability density function from which the \( P_{10} \) low-flow inputs to reservoirs were estimated.

3.6. Natural Lake Storages

The authors are unaware of a compendium of spatial and hydrologic information explicitly on naturally formed lakes in the United States, as opposed to lakes created by dam construction. In lieu of a comprehensive data set on these sources, this study only includes natural lake storages specifically identified as water sources by urban utilities. Of the 14 lakes identified as urban sources, data on the primary use, location, surface area, and mean depth were collected from independent sources, and when unknown, lake volume was approximated using the surface area and average reported depth. Lakes were assumed to be managed to ensure supply over a 50-year planning horizon [Graedel and Klee, 2002] reducing the mean annual lake volume available (\( \mu_L \)) to 1/50th of the average total available. Additional assumptions regarding user access were similar to those of reservoirs, where supplies were equally divided across users and between purposes, with the exception that an ecological “set-aside” was added to each source to account for the maintenance and preservation of natural ecosystem function in addition to any other uses listed. In cases where no specific purposes could be identified, the annual available volume was divided equally between “water supply” and “ecological set-aside” purposes. In instances where more than one urban area utilized a lake as a primary source of water, this modified mean annual volume was equally divided across the users.

Variability in lake storage was also unavailable and therefore estimated based on the \( P_{10} \) exceedance probabilities for each lake’s inflows. Inflow data, including the mean annual flow (\( \mu_Q \)) and flow variance (\( \sigma_Q^2 \)), were available for the five Great Lakes only. Annual inflow exceedance frequencies for the other 11 lakes considered here were estimated based on measurements of inflow from local precipitation. As basin information for these lakes was not readily available, these values were simply estimated as mean local precipitation over the lake surface area.

3.7. Groundwater Recharge and Storage

Aquifer information collected from USGS (Principal aquifers of the 48 conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands, 2008b, http://www.nationalatlas.gov/ml�/aquifrp.html) included the location and rock type of the major water-supplying aquifers, while estimates of hydraulic conductivity and transmissivity for each aquifer were obtained from a supplementary regional groundwater analysis (USGS, Estimated mean annual natural groundwater recharge in the conterminous United States, USGS Water Resources NSDI Node, 2003, http://water.usgs.gov/GIS/metadata/usgswrd/XML/rech48grd.xml#stdorder). Data on aquifer saturated thickness, when available, were from USGS (http://water.usgs.gov/GIS/metadata/usgswrd/XML/qsitesdd.xml) \((n = 17)\). For the 22 aquifers where saturated thickness was unknown, the geometric mean of the reported aquifer saturated thickness data (61 m) was used as a substitute.

Naturally available groundwater was defined as all non-fractured aquifers that intersected more than 5% of the UAB. Fractured-rock aquifers, whose productivity can be extremely variable at the local scale, were excluded since information from this data set was not of sufficient resolution to quantify availability at specific urban locations. Contributions from fractured-rock aquifers were only included when listed as a primary source by an urban utility \((n = 9)\).

While 65 urban areas utilize principal aquifers for water supply, 54 also listed smaller, surficial aquifers as water sources. No collective database is available for these nonprincipal aquifers, and current data regarding each are often localized, limited in its coverage, and/or difficult to access. Therefore, in cases where utilities cited a nonprincipal aquifer as a primary source, yet the urban area also intersected a principal aquifer, the principal aquifer data were substituted for the smaller aquifer at the risk of perhaps greatly overcompensating for groundwater availability in some areas.

To estimate the volume of groundwater available to urban areas, the following assumptions were made: (1) water withdrawals are of adequate drinking water quality and are made from the center of urban areas, (2) aquifers are unconfined, (3) pumping rates, groundwater recharge and heads are constant, (4) the cone of depression from pumping is symmetric, and (5) drawdown at the pumping well, \( b \) \([\text{L}]\), near the well at radius \( R \) \([\text{L}]\) is constrained to a fraction of the aquifer total unimpacted saturated thickness, \( B \) \([\text{L}]\), at a distant point (radius \( R \) \([\text{L}]\)) from the well. That

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<th>Region</th>
<th>Total Reservoirs</th>
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*For regions where \( > 10\% \) of reservoirs associated had inflow information, correction factors were developed to reconcile differences between the gaged data and the inflows calculated using the regional model. Here, regions correspond to the USGS HUC-2 watershed delineations.
where \( B \) and \( C_22 \) were used. The volume of groundwater naturally available to each urban area \( (\mu_g) \) was then determined from the Thiem equation (Gupta, 2010):

\[
\mu_g = \frac{\pi k}{\ln \left( \frac{R}{r} \right)} \left( B^2 - (\alpha B)^2 \right) + \frac{w}{2k} \left( R^2 - r^2 \right),
\]

(7)

where \( k \) is the hydraulic conductivity \( [L^1T^{-1}] \), and \( w \) is the groundwater recharge rate \( [L^1T^{-1}] \). Captured groundwater was only calculated for urban areas that listed groundwater as part of their supply portfolio and had a mean annual available volume less than \( D \). For these cases, the volume of water captured, or pumped in excess of the naturally available groundwater, was equal to the difference between \( D \) and the mean annual water availability.

(32) Groundwater recharge, calculated as the product of mean annual baseflow and runoff, was obtained from a 1 km resolution raster data set (USGS, http://water.usgs.gov/GIS/metadata/usgswrd/XML/rech48grd.xml#stdorder). Individual grid values were averaged by aquifer to calculate an annual mean recharge \( (\mu_r) \) and recharge variability \( (\sigma_r^2) \). These data were then used to calculate \( P_{10} \) low-flow/drought-reduced recharge to groundwater storages.

4. Results

4.1. Water Availability Assessments

(33) Hydraulic-based estimates of water availability were compared to the commonly used runoff-based available estimates for each of the 225 urban areas with sufficient hydrologic information. The mean \( Q^* \) for all urban areas was bounded using \( \pm 1 \) standard deviation (SD) and was considered a region of potential for, but not certainty of, water scarcity issues occurring. The \( Q_R \) and \( Q_H \) for each urban area are shown in Figure 3 as the cumulative urban population, ranked by water availability. For both cases, urban areas falling 1 SD below \( Q^* (Q < 770 \text{ lpcd}) \) were considered at high risk for water scarcity due to their low mean annual availability, whereas urban areas placing 1 SD above \( Q^* (Q > 2200 \text{ lpcd}) \) were categorized as having few, if any, scarcity issues. Those falling between these two thresholds were classified as being moderately at risk of water scarcity. The median values of the two estimates \( (Q_R = 5400 \text{ lpcd} \text{ and } Q_H = 18,500 \text{ lpcd}) \) were significantly different (Mann-Whitney \( U = 64960, \ p < 0.001 \) (Figure 3)).

[34] Water availability assessments made using the runoff-based method give little consideration to the effects of cumulative river drainage, locally available storage, and/or imported water on urban water provision [Weiskel et al., 2007]. As such, the runoff-based method consistently produces lower volumes of annually available water and finds that nearly half of the U.S. urban population (47%) faces a moderate (27%) or severe (20%) risk of water scarcity (Figure 3). In contrast, the hydraulic-based assessments incorporate cumulative flows, as well as storages and imported supplies—the latter two being important for mediating hydrologic variability. Using the hydraulic-based approach, a substantial decrease of the “at-risk” population occurs—only 17% of the U.S. urban population encounters moderate (13%) or severe (4%) risk of water scarcity.

[32] Groundwater recharge, calculated as the product of mean annual baseflow and runoff, was obtained from a 1 km resolution raster data set (USGS, http://water.usgs.gov/GIS/metadata/usgswrd/XML/rech48grd.xml#stdorder). Individual grid values were averaged by aquifer to calculate an annual mean recharge \( (\mu_r) \) and recharge variability \( (\sigma_r^2) \). These data were then used to calculate \( P_{10} \) low-flow/drought-reduced recharge to groundwater storages.

Figure 3. Comparison of a hydraulic- and runoff-based approach for estimating the total urban population at risk for water scarcity. Urban areas were considered at risk for water scarcity when demands accounted for >40% of the mean annual water available. This risk limit was defined as \( Q^* = 1500 \text{ lpcd} \) (solid vertical line) \( \pm 1 \) SD (dotted lines). Urban areas to the right of the limit were considered to be free of water scarcity issues. Those falling within or to the left of the limit boundaries represent urban areas with moderate and severe water scarcity issues, respectively. Depending on the method used, the severity of water scarcity for a given urban area can shift dramatically. Here, five of the largest urban areas (populations > 10^6) with significant differences between \( Q_H \) and \( Q_R \) are labeled (MIA, Miami, FL; DEN, Denver-Aurora, CO; LAS, Las Vegas, NV; DFW, Dallas-Fort Worth-Arlington, TX; PHX, Phoenix-Mesa, AZ).
Further distinction between the two availability assessments was made by comparing the contributions of local renewable flows to those of cumulative upstream flows, storages, and additional water from imports. When compared to $Q_{H}$, the distribution of $Q_{R}$ values appears truncated at either extreme (Figure 4). These differences occur because $Q_{R}$ values are not feature dependent; they are not necessarily concentrated in hydrologic features such as rivers that are easily accessible to utilities, but rather are expressed as a uniformly distributed source. The highest $Q_{R}$ values are for cities that have access to large storages or river flows representing confluences of upstream sources. When considering minimum availability, the lowest $Q_{H}$ values are higher than corresponding $Q_{R}$ values because cities without major natural water sources have developed imported water sources. From these distinctions, it becomes clear that while local renewable flows are useful for assessing aridity, they do not account for cumulative inputs from rivers, imports, or water held in storage and therefore may not provide reliable estimates of water availability for urban analyses.

Without including hydraulic components, 28 urban areas—including Houston, TX, Fresno, CA, and New York, NY/Newark, NJ—face moderate risk of water scarcity, while 23 urban areas—including Denver/Aurora, CO, Tucson, AZ, and Los Angeles, CA—suffer from severe water scarcity problems. Interestingly, most urban areas with >10,000 lpcd of naturally available water have not acquired substantial volumes of imported water, suggesting that the volume of water required to be “water secure” is an order of magnitude greater than the average water availability accessible to urban areas. Using the runoff-based assessment, 14 urban areas have availabilities that do not meet average urban demands of 600 lpcd. This implies that these areas face perpetual water shortages not from seasonal variability or drought, but rather a perennial, systematic, physical lack of water. Alternately, when imported sources and storages are included using the hydraulic-based method, all U.S. urban areas are found to have enough water available on a mean annual basis to meet this critical threshold. These contrasting assessments not only emphasize the importance of a hydraulic-based approach, but provide some practical context for water scarcity occurs in the United States.

Since runoff-based urban water scarcity observations are closely tied to precipitation, the results from this method show a similar and familiar pattern at the regional level. Urban areas in drier southern and western regions of the nation, such as Phoenix-Mesa, AZ, and San Diego, CA, tend to have lower mean $Q_{H}$ values than those in wetter northern and eastern regions, such as Baltimore, MD, and Duluth, MN. Results using the hydraulic-based assessment only partially reflect this relation to regional precipitation patterns. For example, Los Angeles, CA; San Antonio, TX; and Salt Lake City, UT, all have relatively low $Q_{H}$ because local aridity leads to insubstantial river flows and few nearby natural water storages. However, cities in arid areas such as these have typically developed sizable infrastructure networks to procure and store water resources. These imported sources boost the overall volume of water available. However, because of high costs and long-distance transport difficulties, cities in arid regions are rarely able to acquire distant sources large enough to match the volumes accessible to cities rich in naturally available water.

![Figure 4. Comparison of runoff- and hydraulic-based water availability. Dotted lines represent the water scarcity risk limits ($Q^* \pm 1$ SD). The local renewable flows used to measure $Q_{R}$ provide information about relative aridity, but do not incorporate water available from sources that urban utilities can physically access (i.e., rivers, above/below ground storages, imported sources). Therefore, the total range of renewable flows measured using $Q_{R}$ was relatively restricted when compared to hydraulic-based method. Exclusion of cumulative renewable flows limited the upper range of $Q_{R}$, while buffering minimum water available in water-scarce regions. Additions of storage and imports using the $Q_{H}$ method raised the minimum volume of water available beyond that given using $Q_{R}$ showing that urban areas may compensate for local water scarcity by utilizing storages and importing additional sources, shifting the population at risk from 48% to 16%.](image-url)
[38] Extreme differences of estimated water scarcity, where an urban area was considered to be at low risk using one method, and at high risk using the other, were found for 12% of the U.S. population (19 urban areas). Access to large storages and imports in the form of major aquifers or networked reservoirs moved 18 of these urban areas from a high-risk category under the runoff method to low-risk category using the hydraulic method. Four of these 18 cities have population > 10^6 and are highlighted in Figure 3. In contrast, only one urban area, Miami, FL, trended in the opposite direction. Miami is considered to be at low risk of water scarcity using the runoff-based method, but at high risk when hydraulic components are included. This unique case reflects the importance of storage—while Miami experiences high local runoff and recharge, the accessible aquifer storage volume is small relative to the urban demand. This source is able to sustain the needs of Miami due to rapid aquifer recharge; however, the small storage volume suggests that there is little room for growth or fluctuations in supplies without potential environmental repercussions.

4.2. Water Availability Sensitivity Analysis

[39] A multivariate sensitivity analysis was implemented to examine the relative importance of the parameters impacting the percent of population at risk for water scarcity due to low mean annual availability. The parameters evaluated were (1) minimum river flow \( \mu_{\text{E}} \), (2) groundwater drawdown constraint \( \alpha \), and (3) scarcity threshold \( \gamma \). The method used here is a simplified application of the method of Morris [1991], which is useful for examining simultaneous changes to multiple parameters over a specified range.

[40] Each of the three parameters was varied around the nominal value used in the hydraulic analysis (section 4.1), encompassing a range based on reasonable management possibilities. The minimum river flow \( \mu_{\text{E}} \) is based on the percentile flow allocated and is varied from the nominal value of Q75 down to Q50 and up to Q95. These values correspond to near-pristine ecosystem functionality (Q50) and extreme degradation due to anthropogenic development (Q95) [Smakhtin et al., 2004]. Groundwater drawdown constraints \( \alpha \) and scarcity benchmarks \( \gamma \) were each varied by \(-50\%\) and \(+100\%\) of the nominal values.

Allowable groundwater drawdown limits were therefore set at 5%, 10%, and 20% of the total saturated thickness, and scarcity benchmarks were modified to express a demand-to-available water ratio of 20%, 40%, and 80%. Each of the three values within the range of a particular parameter was tested for all possible combinations of the remaining two parameters. This yielded a suite of nine results for each test, from which the mean and variance of the percent of population at risk was calculated.

[41] Results in Figure 5 show the mean and SD of the percent of the urban population at risk in response to variation of the three parameters of interest. As expected, increasing \( \mu_{\text{E}} \) and \( \alpha \) decreased the number of people potentially at risk, while the reverse was true when these parameter values were decreased. Increasing \( \gamma \) from the nominal value to 80% only minimally decreased the severity of risk, whereas restricting this threshold to 20% produced the strongest effect in the entire sensitivity analysis, increasing the at-risk population by 27% and thereby indicating that this is an important parameter in such evaluations.

[42] The SD of each mean in Figure 5 indicates the extent to which the test parameter is affected by changes in other parameters. The variability associated with the parameters \( \mu_{\text{E}} \) and \( \alpha \) was substantially higher than for \( \gamma \), indicating that the latter has a strong direct effect on results. By contrast, the relatively high variability associated with \( \mu_{\text{E}} \) and \( \mu_{\text{E}} \) indicates interaction effects, likely due to changes in the ratio of \( \gamma \) given the strong effects observed. However, such variability could also be due to nonlinear direct effects, as opposed to interaction effects.

4.3. Water Vulnerability Assessments

[43] Using the results from section 4.1, urban water vulnerability was assessed as a function of the water availability and the susceptibility of urban supplies under low-flow conditions. The boundary between vulnerable and secure urban areas is numerically defined as \( Q^* \) on the x-axis, and as \( \alpha = 1 \) on the y-axis. Here, \( \alpha > 1 \) indicated that under low-flow conditions, inflows were still greater than \( Q^* \) and thus had a relatively low susceptibility, whereas urban areas with \( \alpha < 1 \) inflows are unable to meet mean annual demands under low-flow conditions, indicating relatively

![Figure 5.](image_url)
high susceptibility. Combined, these two boundaries create vulnerability quadrants (Figure 6) three of which are relevant to this study and represent zones of high availability/low variability (type I), high availability/high variability (type II), and low availability/high variability (type III). Urban areas in quadrant I are considered the least vulnerable according to this classification with those in quadrants II and III being moderately and severely vulnerable systems, respectively.

When considering these assessments, it is worth noting that both methods show a strong positive correlation between water availability and low-flow susceptibility (Figure 6), reflecting the fact that low-flow sensitivity is frequently tied to the overall size of the source. Urban areas with a lower $Q$ tend to have fewer natural sources with lower availability. Lower availability sources will inherently have smaller low-flow volumes, restricting the ability of these urban areas to meet $Q/C_3$ requirements. However, the value in this analysis lies not in the observable correlation between $Q$ and $a$, but in the distribution of urban areas between areas of low and high availability and susceptibility.

Using the hydraulic-based assessment, the majority of urban areas (152) fall within quadrant I, indicating that nearly half of the total U.S. population (46%) faces little to no urban water vulnerability issues. Of those remaining, 61 urban areas (38% of the population) were in quadrant II and were classified as “moderately vulnerable,” whereas 10 urban areas (16% of the population) were in quadrant III and were categorized as being “highly vulnerable.” The runoff-based method provides an alternate assessment of urban vulnerability. While approximately half of the urban areas (130) are categorized as having low vulnerability (I), this only accounts for 34% of the total population. The greatest percent of the population resides in moderately (II) vulnerable areas (41%), but comprises only 59 urban areas. Finally, the number of urban areas falling into quadrant III is three times that measured using the hydraulic approach (34) and encompasses 25% of the population.

Of the urban areas found to be most vulnerable (type III) using the hydraulic and runoff-based methods, more than one third of these areas reported relying on regional water projects where imported water is often shared between multiple users, and flowing systems can experience high degrees of variability. Others in this category, such as Los Angeles/Long Beach/Santa Ana, CA, and Salt Lake City, UT, represent locations with little surface water and relatively small available storages of groundwater. Here, both analyses identified areas where intensive water management has had to occur to secure water for urban development, and where vulnerability issues seem more likely.

Lastly, the moderately vulnerable urban areas (type II) highlight where urban vulnerability is perhaps most dangerous. This category contains locations where the mean annual availability is sufficient to meet urban demands. However, issues arise when the low-flow variability associated with each location is considered (Figure 6). Locations with relatively large local renewable flows but small hydraulic inputs, such as Raleigh, NC, and Atlanta, GA, experience low vulnerability (I) using the runoff-based method, but become moderately vulnerable (II) when fluctuations in the hydraulic components are considered. Highlighted in Figure 6 are the 14 cities of population $>10^6$ where highly variable inflows (quadrants II or III) overlap with relatively small inputs from hydraulic sources ($<10D$) using the hydraulic method. These conditions can result in serious water issues during periods of low natural inflows. An excellent

Figure 6. Water vulnerability categories as a function of mean annual water availability ($Q$) and low-flow susceptibility ($a/Q^*$). The severity of vulnerability increases with each successive quadrant number, where quadrants I, II, and III group urban areas with low, moderate, and severe vulnerability issues, respectively. Highlighted are the 14 cities of population $>10^6$ where highly variable inflows (quadrants II or III) overlap with relatively small inputs from hydraulic sources ($<10D$) using the hydraulic method.
example is Atlanta, GA—with relatively poor access to hydraulic inputs as it is located upstream of any major local rivers, and has little to no access to groundwater. Despite being located in a humid climate, Atlanta experienced a major drought in 2007–2008 that resulted in well-publicized water scarcity concerns [Dewan, 2009; Glennon, 2009].

Differences between the runoff- and hydraulic-based methods can be seen in Figure 7, where availability

Figure 7. Water availability and vulnerability of 225 U.S. urban areas based on (top) runoff and (bottom) hydraulic methods. Both methods show that urban areas with relatively lower availabilities are more vulnerable, although the number of highly vulnerable locations is three times higher for the runoff-based method. The number of moderately vulnerable urban areas shown is approximately equal for the two methods, but varies by location. Variation is due in part to the assumptions used in each method. Using the runoff-based method, water supplies are assumed to be solely based on local renewable flows, where humid locations tend to have high availability and low vulnerability. However, results from the hydraulic-based method, based on cumulative flows, storages, and imports, are only weakly tied to regional conditions of humidity. These assessments must factor in assumed environmental constraints for storages, which limit withdrawals from large sources such as groundwater and lakes. The differences between the two methods can be large enough that for some locations relying on natural lake (e.g., Buffalo, NY) or groundwater (e.g., Gainesville, FL) sources, tighter restrictions on the hydraulic sources make these areas more prone to vulnerability issues, despite the overall size of the source.
and vulnerability are shown for all 225 urban areas. Cities in the Northwest experienced no significant changes in either availability or vulnerability between the two methods. However, using the hydraulic method, urban areas in the rest of the West generally improved both in terms of availability and vulnerability, emphasizing the importance of groundwater and regional water distribution systems to urban supply particularly in drier areas. Cities in the eastern half of the United States showed little change in availability, with a notable exception of Miami (described above). However, there was a noticeable redistribution of urban areas considered vulnerable in the Eastern United States from those where low-flow susceptibility arises from renewable sources (runoff method) to those where the inputs to storages during low flows and environmental restrictions on withdrawals from storages are limiting (hydraulic method). When considering water scarcity at the national level, the runoff-based method showed that the percent of the population considered “at risk” in the assessments of availability (47%) and vulnerability (66%) is relatively small. In contrast, the hydraulic method produces a substantially greater disparity between the at-risk populations for availability (17%) and vulnerability (54%). The disparity between hydraulically determined availability and vulnerability may help reconcile the seeming contradiction in the United States between natural water abundance and widespread water scarcity. Most urban areas have acquired sufficient supplies to meet mean annual demands; however, the reliability of these sources under low-flow conditions belies this apparent security in many cases.

Finally, the hydraulic method includes environmental constraints related to minimum flow requirements on rivers and pumping limitations on groundwater that optimally reflect a high level of concern for ecosystem preservation. While ecological allocations are ultimately flexible, the assumptions made here represent a stricter set of standards limiting urban access, and these assumptions impact the availability and vulnerability results. For example, several of the urban areas utilize large storages, such as the Great Lakes or major aquifers. Environmental constraints limit access to these large storages in the hydraulic method, and they therefore do not necessarily significantly decrease vulnerability. While more location-specific information regarding how storages are practically used would add clarity, the true vulnerability of these systems ultimately depends on the environmental or other operational constraints imposed.

4.4. Media Text Analysis

To verify the results of this vulnerability analysis, an MTA was designed to serve as a qualitative proxy for the severity of the vulnerability assessments. The text analysis mined the Google News Archive database to find the frequency with which news articles covering vulnerability issues about specific urban areas occurred. This database search included all forms of news-related media between 1 January 1980 and 31 August 2011 for each urban area. Relative vulnerability was measured by searching this database using a combination of terms most commonly found in a subset of urban water vulnerability-related articles. The number of articles returned for each search string was recorded for every urban area, and the mean number of articles across these searches was then used as a proxy, where higher numbers of article hits indicated higher vulnerability. To control for the failure of each search to capture the exact number of vulnerability-specific articles for each urban area, four different sets of search terms were used: “Water” AND “(1) Restrictions, (2) Conservation and Drought, (3) Crisis, (4) Shortage” AND City, State.

MTAs were performed using both methods of vulnerability classification. Results from these searches (Figure 8) showed that in general, the mean number of articles increased with vulnerability severity, and that the strength of this trend was more pronounced for urban areas classified using the hydraulic-based method. Using a two-way analysis of variance, statistically significant differences within the hydraulic-based method were found in two of the pairwise comparisons (type I versus III, p < 0.001; II versus III, p = 0.003), but not between I and II (p = 0.121). There were no statistically significant differences between the vulnerability categories using the runoff-based method. These results further emphasize the differences between the two methodologies used here; while the search criteria for this proxy were relatively simple, the patterns derived from this analysis suggest that the inclusion of hydraulic features in vulnerability assessments may better reflect the reality of urban water scarcity as reported in the popular press.

5. Conclusions

The American water industry has identified urban water availability as top concern for utilities as of 2008. These concerns reflect the lack of an accurate and standardized method for quantifying urban water availability and vulnerability at the national level. Utilities, the government and academia have all attempted to fill water availability/vulnerability gaps; however, differences in scales and methods remain vast, and accessible data remains sparse. Of the current water availability/vulnerability studies, most assessments have measured these parameters in terms of renewable runoff while ignoring storage components. In reality, storages play an important role in nearly all urban utilities supply portfolios. This study addressed this gap by implementing a hydraulic-based approach for measuring urban water scarcity in which previously unaccounted-for storages and imports were included in the hydrologic analysis. These results were compared to estimates made using the conventional, renewable runoff, approach. The hydraulic-based approach yielded a lower portion of the population as being at risk to urban mean water availability issues (17%) as compared to the runoff-based method (47%). The results of this analysis were found to be most sensitive to variations in water scarcity benchmarks. In particular, tighter restrictions on the scarcity limit yielded the most significant changes in the number of people considered at risk, suggesting that careful consideration should be given to how “scarcity” is defined. Future analyses may find a refined measure of scarcity, rather than the general benchmark used here, to be more useful for identifying how water use within a system affects the sustainability of the urban system.

Hydraulic-based assessments also predicted that over half (54%) of the U.S. population is at risk for water vulnerability, compared to the 66% predicted using runoff-based
methods. Vulnerability results were validated using an MTA of news articles about water scarcity issues in urban areas, showing that the number of news articles increased with the severity of the vulnerability. This pattern was stronger in urban areas classified using the hydraulic-based approach, implying that this method more accurately reflects the issues currently facing urban areas. However, it is worth emphasizing here that these vulnerability estimates were made using historical low-flow information, which may become a less-descriptive measure of system extremes as climate change continues to alter the spatiotemporal pattern of local, renewable flows. As such, further development of alternate measures of vulnerability will be critical for future urban sustainability efforts.

In this analysis, the differences revealed between the two methods for quantifying urban water expose the potential problems associated with measuring scarcity using only renewable sources of water, particularly when trying to practically assess resources for management-related purposes. This study not only highlights differences between these two methods, but also illustrates the importance of including both local runoff and hydraulic features as components of the urban water budget. Runoff-based assessments are more useful for identifying areas where urban demand is greater than the renewable water supply (i.e., arid areas) and thus where water storage depletion may be occurring. However, also of critical importance is the storage or imports available to urban areas. This study more clearly defines how both availability and vulnerability dictate urban water scarcity. In particular, the hydraulic-based vulnerability analysis identified a group of urban areas that have ample water available on a mean annual basis, but are particularly vulnerable to fluctuations in availability due to limited hydraulic inputs. In comparison, locations with access to large storages and/or imports appear to have more flexibility to adapt to hydrologic variability, even when the renewable water supplies are insufficient to meet demands on a mean annual basis. This is not to say that mining storages or importing distant water supplies are necessarily sustainable strategies for meeting urban water demands, but rather including these hydraulic components in water sustainability assessments provide better context for understanding the nature and severity of urban water scarcity issues.

Water availability and vulnerability play a critical role in defining and implementing sustainable water management practices, yet obstacles to an accurate assessment still remain. While these results offer insight into urban water sustainability issues, they are not meant to be a comprehensive analysis of any given urban area. They do not directly account for institutional or legal controls on water management and are subject to data limitations since several variables needed to make accurate assessments of hydraulic-based water availability and vulnerability are either unavailable, or existed only in very local, or very general terms. As a result, the assumptions required to fill these data gaps (i.e., reservoir/lake allocations) may not be accurate representations in all cases, potentially leading to inaccurate assessments in some areas where data are sparse. For instance, equal allocation of Lake Mead’s total reservoir volume between its designated purposes implies that the city of Las Vegas, NV, received substantially more water than it has access to in reality, thus underestimating its potential water scarcity issues. In addition, variability in resources is a critical issue for urban centers. This is especially true for those in more humid regions where allocation restrictions are only beginning to become more prevalent. As urban water managers increasingly recognize

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**Figure 8.** Comparison of estimated water vulnerability using a MTA where error bars represent ±1 SD. Hydraulic- and runoff-based measures of water vulnerability were compared to assess how well each method captures the severity of water vulnerability as reflected by the popular press. The hydraulic-based method more clearly defined differences between vulnerability categories than the runoff-based method, revealing significant differences between low (I) and severe (III) \( (p < 0.001) \) and moderate (II) and severe (III) categories \( (p = 0.003) \), whereas no significant differences were reported between any categories measured using the runoff-based approach.
variability as a major driver of water scarcity, many may find that water resources need to be increasingly managed in collaboration with neighboring water users, as increasing demands reduce the buffering capacity of water sources. Urban areas may find that historical infrastructure and management techniques may not be flexible enough to adapt to modern problems of fully allocated resources under varying conditions. New policies of water conservation, recycling, and monitoring could reduce these potential stresses. Finally, standardized assessments within a national benchmarking framework could be a useful tool for decision makers not only at the local urban level, but would help water managers at all levels better understand how and where water scarcity issues arise. Despite these constraints, this study nonetheless demonstrated that a comprehensive national water availability and vulnerability analysis that accounts for hydraulic infrastructure is possible, insightful, and necessary if urban systems are to manage water sustainably.

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References


