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Water on an urban planet: Urbanization and the reach of urban water infrastructure

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ABSTRACT

Urban growth is increasing the demand for freshwater resources, yet surprisingly the water sources of the world's large cities have never been globally assessed, hampering efforts to assess the distribution and causes of urban water stress. We conducted the first global survey of the large cities' water sources, and show that previous global hydrologic models that ignored urban water infrastructure significantly overestimated urban water stress. Large cities obtain 78 ± 3% of their water from surface sources, some of which are far away: cumulatively, large cities moved 504 billion liters a day (184 $km^3 yr^{-1}$) a distance of 27,000 ± 3800 km, and the upstream contributing area of urban water sources is 41% of the global land surface. Despite this infrastructure, one in four cities, containing $4.8 ± 0.7 trillion in economic activity, remain water stressed due to geographical and financial limitations. The strategic management of these cities' water sources is therefore important for the future of the global economy.

1. Introduction

Urbanization is one of the most significant trends of the 21st century, affecting global economic development, energy consumption, natural resource use, and human well-being (Brown et al., 2009; Elmqvist et al., 2013; Fitzhugh and Richter, 2004; Jenerette and Larsen, 2006; Lederbogen et al., 2011; McDonald, 2008; McDonald et al., 2011a,b, 2013; Montgomery, 2008). Globally, 3.6 billion people live in urban areas (UNPD, 2011). The next few decades will be the most rapid period of urban growth in human history, with 2.6 billion additional urban dwellers expected by 2050 (UNPD, 2011). All these new urban dwellers will need water, but surprisingly little is known globally about where large cities obtain their water or the implication of this infrastructure for the global hydrologic cycle (McDonald et al., 2011b; Padowski and Jawitz, 2013).

Past research has shown that as cities grow in population, the total water needed for adequate municipal supply grows as well (Bradley et al., 2002; Falkenmark and Lindh, 1974; Falkenmark and Widstrand, 1992; McDonald et al., 2011a; Postel et al., 1996). This increase in total municipal water demand is driven not just by the increase in urban population, but also by a tendency for economic development to increase the fraction of the urban population that uses municipal supply rather than other sources such as local wells or private water vendors (Bartlett, 2003; Bhatia and Falkenmark, 1993). Indeed, increasing access to municipal supply for the world's poor is one of the Millennium Development Goals, since municipal supply is generally cleaner and safer than other water sources (Howard and Bartram, 2003). Moreover, the economic development that generally goes along with urbanization increases per-capita water use, as new technologies such as showers, washing machines, and dishwashers increase residential

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use of water (McDonald et al., 2011a). The overall increase in total municipal water demand causes cities to search for new adequate, relatively clean water sources, leading to the creation of sometimes quite complex systems of urban water infrastructure (Alcott et al., 2013; Brown et al., 2009; Chau, 1993).

Cities by their nature spatially concentrate the water demands of thousands or millions of people into a small area, which by itself would increase stress on finite supplies of available freshwater near the city center (McDonald et al., 2011a). However, cities also represent a concentration of economic and political power (Bettencourt et al., 2007), which cities use to build urban water infrastructure to satisfy their demand. As this infrastructure can go out far from the city center, or exploit new sources of surface water, groundwater or desalination, it often helps cities escape water stress. Our theoretical approach in this paper was to contrast these two phenomena (concentration of water demand and concentration of power), to examine when urban infrastructure is sufficient to escape water stress and when it is insufficient. We hypothesized that geographical limitations on water availability will affect patterns of urban water scarcity – some cities are simply in relatively dry climates, or located far from large water sources, and thus may have trouble obtaining enough water. We also hypothesized that financial limitations in the construction of infrastructure will affect patterns of water scarcity, with richer cities with more resources able to construct more robust urban water infrastructure and thus escape water scarcity.

We conducted the first global survey of the water sources of large cities (population >750,000), surveying the 50 largest cities and a representative sample of more than a hundred other large cities. Large cities contain 1.5 billion people, one in every three urbanites (UNPD, 2011). We use our survey to make statistical estimates of water stress for all large cities on Earth. The specific research questions we aimed to answer were:

1) Does accounting for urban water infrastructure in global hydrologic models significantly alter the estimate of the population living with urban water stress?
2) How big is the scope of urban water infrastructure globally, in terms of the amount of water used, how far it is transported by canals, and the total area of the Earth's surface that contributes water to urban sources?
3) What factors increase the likelihood of a city being water stressed, even after accounting for its urban water infrastructure?

2. Materials and methods

For each point on the Earth's surface, we used information from global hydrologic models to calculate the ratio of water withdrawals to the water available at that point. This ratio of water use/available is our primary metric of water stress in this paper (Falkenmark and Lindh, 1974; Falkenmark and Widstrand, 1992; Gleick, 1996; Howard and Bartram, 2003; Ward and Pulido-Velazquez, 2008). For surface water stress we used data from two global models of surface hydrology and water use: WaterGAP (Alcamo et al., 2003; Döll et al., 2003, 2012) and the Water Balance Model (Vörösmarty et al., 1998; Wisser et al., 2010). For groundwater stress, we used the previous analysis of the groundwater footprint (Gleeson et al., 2012) which uses data from PCR-GLOBWB (Wada et al., 2012), another global hydrologic model combined with national-scale estimates of groundwater abstraction. All three global hydrologic models also include downscaled estimates of water use, as described in the section on each model.

Unless noted otherwise, we quote values of surface stress derived from the Water Balance Model (WBM), which gives generally lower values of water stress than the WaterGAP model. Note that water stress ratings calculated with both models are available in Supplementary Table 1, so readers can compare the results of the WBM and WaterGAP model if they wish.

2.1. Selecting target cities

The goal of this study was to characterize the water stress of urban agglomerations greater than 750,000 people, which are surveyed as part of the World Urbanization Prospects (UNPD, 2011) report conducted by the United Nations Population Division. The WUP lists the past and current population of each urban agglomeration greater than 750,000 people (cumulatively, 1.5 billion people in 2010). The WUP uses urban agglomeration as their level at which to report data, with one urban agglomeration perhaps containing more than one city proper, the administrative unit at which municipalities are governed (Montgomery, 2008; Montgomery et al., 2003). In the remainder of this section, we use "city" as a synonym for the urban agglomeration level of the WUP, reserving the term "city proper" for smaller units of urban organization.

In the first phase of our project, we targeted the 50 cities with largest population for data collection. We also targeted primary cities, the largest urban agglomeration in a country, if they were larger than 750,000 people. In the second phase, since it was not feasible to collect information on all cities in the WUP list, we targeted a sample of cities. This sample was stratified into categories by city size (< 1 million, 1–2.5 million, 2.5–5 million, or >5 million), crossed with geographic region (Asiatic Russia, Australia/New Zealand, Caribbean, Central America, Central Asia, Eastern Africa, Eastern Asia, Eastern Europe, European Russia, Middle Africa, Northern Africa, Northern America, Northern Europe, Polynesia, South America, Southeastern Asia, Southern Africa, Southern Asia, Southern Europe, Western Africa, Western Asia, Western Europe). The target number of cities we aimed to survey in each category was proportional to the number of urban agglomerations in that category. Within each category, urban agglomerations from the WUP were randomly ordered into a list, and we attempted to survey urban agglomerations in that order, beginning at the top of the list. Not all urban agglomerations had easily obtainable data, however, and if it was not possible to find information on one agglomeration we searched for the next agglomeration on the list. In some cases, particularly in the United States, one urban agglomeration was made up of multiple cities proper, each with a separate water supply system, and we mapped each separate supply system where the city proper was greater than approximately 100,000 people.

Our sample of cities therefore oversampled in some categories and undersampled in others, as cities in some categories were harder to find water source information for and were sampled at a lower proportion than those in other categories. Cities with large populations were easier to find data for, while cities in the <1 million category were harder. Some countries like China were difficult to find data for, while others like the United States (Padowski and Jawitz, 2013), Brazil, and India had excellent, easily available data on water sources. We use post-stratification during our statistical analysis (see below) to account for the potential bias due to missing data.

For each city on our target list, we used web searches in the primary language used in the city to find the names of the water utilities or agencies that supply water. Once that name was obtained, we usually found annual reports or information supplied to national governments that lists water sources and the amount of water withdrawn. In some cases, we had to use sources of lower certainty, such as the website of the water utility, which often list water sources. Once the place names of water sources were identified, we geolocated the sources. Unique places names were identified in Google Maps or other geographical atlases. In some cases, a text description of a source (e.g., "three miles upstream of the city along the same river that flows through the city") was mapped in a geographical information system (ArcGIS 10.2).

The resultant database of city water sources and associated attributes, termed the City Water Map (CWM), has a hierarchical structure. Variables collected at the city level include the WUP urban agglomeration to which it belongs, which allows the processing of data at the urban agglomeration level of resolution (see below). Data collected at the utility level included the name of the utility, the population it served, and the total volume of water it supplies. Utilities rely on one or more water diversions, and the data collected at the diversion level included its name, its spatial location, its type (surface, groundwater, saline water, etc.), and the volume diverted by the utility from that diversion.

For each withdrawal point, the spatial location was recorded as accurately as possible in an ArcGIS geodatabase. For surface freshwater withdrawal points, their location had to be adjusted ("snapped") to match the underlying hydrographic river system, in this case represented by the global high resolution hydrographic dataset HydroSHEDS (Lehner et al., 2008). The HydroSHEDS digital elevation model was created from NASA's Shuttle Radar Topographic Mission (SRTM) (Farr et al., 2007) and further processed to ensure correct hydrographic flow paths. If the snapping adjustment step is not performed, small spatial errors in the location of a point could lead to large errors in the estimation of the available water. First, we selected withdrawal points within 10 km of the coast, and manually adjusted their location to ensure that in the underlying hydrographic system they were not falling on areas that are considered saline water. Second, for withdrawal points on lakes, we adjusted the location to be at the outflow of the lake, defined as the lowest point of the lake feature as defined in a global database of lakes, reservoirs, and wetlands (GLWD) (Lehner and Döll, 2004). This correction allows the watershed of the lake and its corresponding water availability to be correctly derived. Finally, using the Snap Pour Point command in ArcGIS, we adjusted the location of withdrawal up to 5 cells (2.5 km) to match the point of greatest flow accumulation. After this procedure, the adjusted water source information was intersected with our three hydrologic models. For part of our analysis, we calculated to the nearest water body with more than 10, 100, and 1000 million liters per day of available water.

2.2. Data processing

For this paper, the fundamental unit of analysis was the urban agglomeration, as defined by the UNPD WUP. In order to conduct the analysis at this level, attribute information collected at the level of a water diversion point or water utility had to be aggregated to the urban agglomeration level. Some urban agglomerations contained multiple cities proper, and we consulted the UNPD WUP documentation to correctly assign each city proper to the correct urban agglomeration. For most water diversion points we knew the volume of water withdrawn annually, and for any attribute collected at water diversion level the average value for the urban agglomeration was calculated as the volume-weighted average of all diversions that service that urban agglomeration. For cities where diversion-specific water withdrawal information was not available, for any attribute collected at water diversion level the average value for the urban agglomeration was calculated as the simple average of all diversions.

2.3. Models of water stress

2.3.1. WaterGAP

One source for information on surface water stress was the WaterGAP model. The global integrated water model WaterGAP consists of two main components: (1) a water balance model to simulate the characteristic macro-scale behavior of the terrestrial water cycle in order to estimate water availability (Alcamo et al., 2003; Döll et al., 2003, 2012) and (2) a water use model to estimate water withdrawals and consumptive water uses for agriculture, industry and domestic purposes (Aus der Beek et al., 2010; Flörke et al., 2013). The model operates on a $0.5 \times 0.5^{\circ}$ resolution.

Based on the time series of climatic data, the hydrological model calculates the daily water balance for each grid cell, taking into account physiographic characteristics like soil type, vegetation, slope, and aquifer type. Runoff generated on the grid cells is routed to the catchment outlet on the basis of a global drainage direction map (Döll and Lehner, 2002), taking into account the extent and hydrological influence of lakes, reservoirs, dams, and wetlands.

Spatially distributed sectoral water withdrawals and consumption are simulated for the five most important water use sectors: irrigation, livestock based agriculture, industry, thermal electricity production, and households and small businesses. Countrywide estimates of water use in the manufacturing and domestic sectors are calculated based on data from national statistics and reports and are then allocated to grid cells within the country based on the geo-referenced population density and urban population maps (Flörke et al., 2013).

The amount of cooling water withdrawn for thermal electricity production is determined by multiplying the annual thermal electricity production with the water use intensity of each power station, respectively. Input data on location, type and size of power stations were based on the World Electric Power Plants Data Set. The water use intensity is impacted by the cooling system and the source of fuel of the power station. Four types of fuels (biomass and waste, nuclear, natural gas and oil, coal and petroleum) with three types of cooling systems (tower cooling, once-through cooling, ponds) are distinguished (Flörke et al., 2012).

Net and gross irrigation requirements, which reflect an optimum supply of water to irrigated plants, are computed based on digital global map of irrigated areas (Siebert et al., 2005, 2006) as a starting point for simulations. The model simulates cropping patterns, growing seasons and net and gross irrigation requirements, distinguishing 21 crop types (Aus der Beek et al., 2010). Water withdrawals for livestock are computed by multiplying the number of animals per grid cell by the livestock-specific water use intensity (Alcamo et al., 2003).

Any value greater than 0.4 on our water stress metric (use/available) was considered water stressed. Many other surface water analyses have used a threshold of 0.4; see the discussion in Vörösmarty et al. (2000) for more detail on the history and use of this threshold.

2.3.2. WBM

Another source for information on surface water stress was output from the Water Balance Model Plus (WMB) (Vörösmarty et al., 1998; Wisser et al., 2010). The WBM is a modeling platform operating on simulated topological gridded river networks at various resolutions (0.5° spatial resolution in this study). The underlying simulated hydrologic network varies in its routing of water from that used by WaterGAP, with multiple flow paths allowed in the WBM model. WBM calculates components of the hydrological cycle on a grid cell by grid cell basis by partitioning each grid cell into an irrigated and a non-irrigated fraction and computing the water and vapor fluxes in each grid cell as the area-weighted sum of the two components. Irrigation water demand in the irrigated fraction of the grid cell is computed for individual crops, distributed globally using global datasets of croplands and aggregated crop types.

WBM distinguishes between large reservoirs that alter the horizontal transport of water through the river network and small reservoirs that are located in grid cells with irrigation. Water release from large reservoirs is calculated as a function of reservoir capacity, inflow, and reservoir storage and can augment river flow during low-flow periods from which irrigation water can be abstracted. Small reservoirs in WBM are assumed to collect part of the estimated surface runoff from the non-irrigated part of the grid cell and partially supply the estimated irrigation water requirement in the irrigated fraction of the grid cell (Vörösmarty et al., 1998; Wisser et al., 2010).

Total water availability of surface water sources at each 0.5° grid cell on the globe is estimated, after accounting for processes of precipitation, evapotranspiration, irrigation and infiltration to groundwater. Human water withdrawals and return flows for domestic and industrial water uses are simulated, with country-level water withdrawal information based on the FAO Aquastat dataset (FAO, 2013) downscaled to the 30-min grid cell resolution using a spatially distributed global population dataset (Balk, 2009; CIESIN et al., 2004).

For each grid cell on the Earth's surface, we used information from both WaterGAP and WBM to calculate the ratio of water withdrawals upstream to the surface water available at that grid cell. This ratio of water use/available is our primary metric of water stress in this paper, a common water stress metric although by no means the only one used in the literature (Falkenmark and Lindh, 1974; Falkenmark and Widstrand, 1992; Gleick, 1996; Howard and Bartram, 2003; Ward and Pulido-Velazquez, 2008). We did not include estimates of natural flow requirements in our analysis, the amount of surface water flow that is necessary to retain healthy freshwater ecosystems, because there is considerable scientific uncertainty about the appropriate natural flow requirements, which is highly variable spatially and temporally. As with the WaterGAP model, any value greater than 0.4 on our water stress metric was considered water stressed. WBM estimates of water stress are slightly lower than for WaterGAP, and unless noted in the text of the paper we present WBM values, as they are more conservative.

2.3.3. Groundwater

Groundwater stress was studied for regional aquifers by Gleeson et al. (2012) using the groundwater footprint methodology. Here we summarize and reiterate the methodology from previous descriptions. The groundwater footprint (GF) is defined as

$$GF = \frac{C}{R - E} \times A$$

where C, R and E are respectively the area-averaged annual abstraction of groundwater, recharge rate including artificial recharge (from irrigation), and the groundwater contribution to environmental streamflow, all in units of L/T such as m/day (Gleeson et al., 2012). A (units of L^2 such as m^2) is the areal extent of any region of interest where C, R and E can be defined. Environmental flow (E) is the quantity of groundwater that needs to be allocated to surface water flow (e.g., baseflow) to sustain ecosystem services including vegetation (e.g., forest), which is most important during low flow conditions (Smakhtin, 2001; Smakhtin et al., 2004).

Groundwater abstraction, C, was calculated from reported country statistics of year 2000. Since the exact locations where groundwater is abstracted by wells are not known for most of the countries, we downscale country-based groundwater abstractions from the IGRAC GGIS database (International Groundwater Resources Assessment Centre; http://www.un-igrac.org/), indexed for the year 2000, by taking the available surface freshwater deficit into account (Wada et al., 2012).

Groundwater recharge, R, was calculated using PCR-GLOBWB, a global-scale hydrologic model that includes an estimate of return flows from irrigation. It is a grid-based model that represents the terrestrial part of the hydrological cycle. For this study it was implemented with a daily time step and a spatial resolution of 0.5° (for more information, see Van Beek et al., 2011; Van Beek and Bierkens, 2009; Wada et al., 2014). The soil column is vertically structured into two soil layers, representing the top and subsoil with a finite depth of maximum 0.3 and 1.2 m respectively, and a third, underlying groundwater layer. The first two layers contain a partly unsaturated zone whereas the third layer has an infinite storage capacity for saturated groundwater storage only. Depending on the gradient present between these layers, the vertical exchange of moisture is downward by percolation and upward by capillary rise. The net positive downward flux from the second to the third layer represents the groundwater recharge to the third layer. To account for the artificial groundwater recharge due to irrigation that possibly mitigates groundwater depletion in areas of large irrigation water withdrawals (Döll et al., 2012), we used the data from Wada et al. (2012).

Environmental flows, E, is considered to be the streamflow contribution from the renewable groundwater (i.e., baseflow) is essential for ecosystem services, sustaining freshwater habitats and associated ecosystems, in particular during low-flow conditions when the contribution from other sources is small. To include this essential aspect of groundwater resources in our analysis in addition to the mere supply of human demand, we identified the environmental flow conditions as the monthly streamflow that is exceeded in 90%, Q_{90}, of the simulated cases over the period 1958–2000. Although environmental flow requirements are best determined by detailed hydroecological data and multidisciplinary expert consultation (Poff et al., 2009; Smakhtin et al., 2004), to be consistent in our analysis we assume that E is a fraction of R for a basin, following Gleeson et al. (2012). To calculate this fraction, the ratio of Q_{90} (the monthly streamflow exceeded 90% of the time, which we consider the low flow), to Q_{Avg}, the long-term average streamflow, is used.

The quantities of R, E and C were aggregated over previously mapped aquifers (BGR/UNESCO, 2008) with a known areal aquifer extent (A_A). The groundwater footprint method is essentially a steady-state aquifer water balance so GF/A_A ratios greater than 1 indicate aquifer outputs are greater than aquifer inputs, suggesting groundwater stress (Gleeson et al., 2012). We note that as a steady-state calculation the groundwater footprint does not include the transient response of groundwater systems to abstraction such as decreased baseflow or increased recharge, as occurs during groundwater development (Aeschbach-Hertig and Gleeson, 2012). Also as a long-term, steady-state calculation, the groundwater footprint does not quantify sub-annual or even interannual groundwater stress. Therefore the effect of extremely seasonal climates is not incorporated. In these cases other metrics such as seasonal or annual water table elevations may be an additional useful metric (CGWB, 2011).

Our index of water stress for groundwater is similar to that for surface water, and is defined as groundwater extraction in an aquifer divided by recharge in that aquifer. Note that the stock of accumulated groundwater in aquifers can be quite substantial, so locally unsustainable use of groundwater can continue for potentially several decades until the stock of groundwater is completely depleted. In our analysis, a city's groundwater supply is defined as water stressed if abstraction/recharge >1, following the analysis of Gleeson et al. (2012).

2.4. Other ancillary data sources

Topographic information used as ancillary variables in this analysis was derived from the HydroSHEDS 15s global dataset (Lehner et al., 2008). Upstream source watersheds were defined for all surface water diversion points, using the Watershed command in ArcGIS with the "snapped" water diversion points (described above).

We used information in the G-Econ 3.0 database (Nordhaus et al., 2012) to capture information on the level of economic development in each city, and to quantify the potential financial limitation some cities face in building their water infrastructure. The G-Econ Database on Gridded Output (Gridded Economic Conditions) project assembles the best available subnational sources of gross income, and is used in this study for the calculation of economic activity in water stressed cities. This information, divided by total population numbers taken from the GPW dataset, provides average per-capita income estimates, which we calculated for each urban agglomeration in our study. This approach allows for an examination of the different level of economic activity in cities; cities in coastal China, for instance, have much higher per-capita income than cities in western China. We used this G-Econ per-capita information to classify cities based on the World Bank categories of economic development: low income, \$1035 or less; lower middle income, \$1036–\$4085; upper middle income, \$4086–\$12,615; and high income, \$12,616 or more (amounts in US2005\$, corrected for purchasing power parity).

Finally, to capture differences in the potential geographical limitation cities face in finding water, we calculated a set of ancillary variables. We calculated the distance from each city centroid to the nearest potential unstressed water source that is greater than a critical volume threshold. Three volume thresholds were used: 100 million liters per day (MLD), 1000 MLD, and 10,000 MLD. An equivalent calculation was done for both the WBM and WaterGAP water stress estimates. The distances required to reach a potential unstressed source is highly correlated between the two models, and we have used the WBM distances in the statistical analyses below.

2.5. Statistical analysis

To correct for any potential bias in the cities included in our sample, and correctly estimate summary statistics for the entire set of cities greater than 750,000 people, we used post-stratification weights (Jagers et al., 1985). Post-stratification is a common technique to adjust for nonresponse in surveys, which uses auxiliary information on the group being studied to reduce the bias and improve the precision of sample estimates. In our case, we used city size and geographical region, which are known for all cities in the UNPD WUP, as our auxiliary information in post-stratification. This technique gives slightly higher weight in our analysis to sampled cities in categories where we had less sample coverage (e.g., East Asia). These post-stratification weights were used in all statistical models and in the construction of all figures. The overall effect on our results was minor – in most cases, the difference between a metric calculated with the post-stratification weights and without was only a few percent.

3. Results

Cities have built extensive urban water supply systems, often relying on dozens of sources hundreds of kilometers distant (Fig. 1a). If one ignores this urban water infrastructure and just assumes urban dwellers obtain water near where they live, as previous hydrologic modeling efforts have, $39 \pm 4\%$ of urban dwellers would be estimated to be in water stress. This is a substantial overestimation of the prevalence of water stress (Fig. 1B). Taking into account urban water supply infrastructure lowers this figure, with $25 \pm 4\%$ of large cities in water stress. In other words, the concentration of economic and political power is sufficient to construct infrastructure to escape water stress approximately one-third the time.

Our study provides the first estimate of the reach of urban water infrastructure. Four in five ($78 \pm 3\%$) urbanites in large cities, some 1.21 ± 0.05 billion people, primarily depend on surface water sources. The remainder depend on groundwater ($20 \pm 3\%$ of urbanites) or, rarely, desalination ($2 \pm 2\%$ of urbanites). The urban water infrastructure of large cities cumulatively supplies 668 billion liters daily ($244\ km^3\ yr^{-1}$). Of this, 504 billion liters daily ($184\ km^3\ yr^{-1}$) comes from surface sources, and that water is conveyed over a total distance of $27,000 \pm 3800$ km. Land use in upstream contributing areas affects the raw water quality and quantity of surface water sources. While large cities only occupy 1% of the Earth's land surface (CIESIN et al., 2004), their source watersheds cover 41% of that surface (Fig. 2), so the raw water quality of large cities depends on the land-use in this much larger area.

The net effect of urban water infrastructure is to homogenize global flows. Our survey found that $12 \pm 2\%$ of large cities use cross basin transfers, collectively moving 83 ± 15 billion liters per day ($30 \pm 5\ km^3\ yr^{-1}$). As most transfers are from wetter basins to dry basins, this homogenizes global flows (Fig. 2). Some basins, such as the Colorado and the Yangtze, are net donor basins, where more water is transferred to other basins for use by cities than is transferred in. Conversely, some basins gain water through urban transfers (Fig. 2). Major urban water transfers are shown in Table 1.

Despite all this urban water infrastructure, many cities remain in water stress (Fig. 1C). One quarter ($25 \pm 4\%$) of the population in large cities, or 381 ± 55 million people, have water supplies that are stressed (WaterGAP estimate: $34 \pm 4\%$, 527 ± 62 million people). The rate of water stress is similar between municipal systems relying on surface ($22 \pm 3\%$ stressed, WaterGAP estimate $34 \pm 5\%$) and groundwater ($39 \pm 12\%$ stressed). A list of water stressed cities (Table 2) includes both cities in developed countries (e.g., United States), and developing countries (e.g., India), as well as both surface (Delhi) and groundwater (Mexico City) dependent cities.

We estimate that the roughly one-quarter of large cities in water stress contain $\$4.8 \pm 0.7$ trillion of economic activity, or $22 \pm 3\%$ of all global economic activity in large cities. This large amount of economic activity in large cities with insecure sources of water emphasizes the importance of sustainable management of these sources not just for the viability of individual cities but for the global economy. Put another way, this \$4.8 trillion in economic activity directly or indirectly depends on the supply of 167 billion liters of water per day ($61\ km^3\ yr^{-1}$) to these cities. Finding ways to maintain this water supply over time is thus of considerable economic importance.

Our analysis did not consider the amount of flow needed in surface water bodies to maintain freshwater biodiversity. Inclusion of such an environmental flow requirement would necessarily increase the number of cities in water stress, since it sets aside a portion of river flow for nature and therefore reduces flow available for appropriation by people. While inclusion of ecological realistic, basin-specific environmental flows requirements is a complex process beyond the scope of this manuscript (Poff et al., 2010), we used the simple threshold of 0.3 for the Water Stress Index suggested by Smakhtin et al. (2004). Using this threshold in effect sets aside 25% of available flow for the environment. Inclusion of this simple environmental flow requirement raises the fraction of urbanites in large cities in water stress to $29 \pm 4\%$

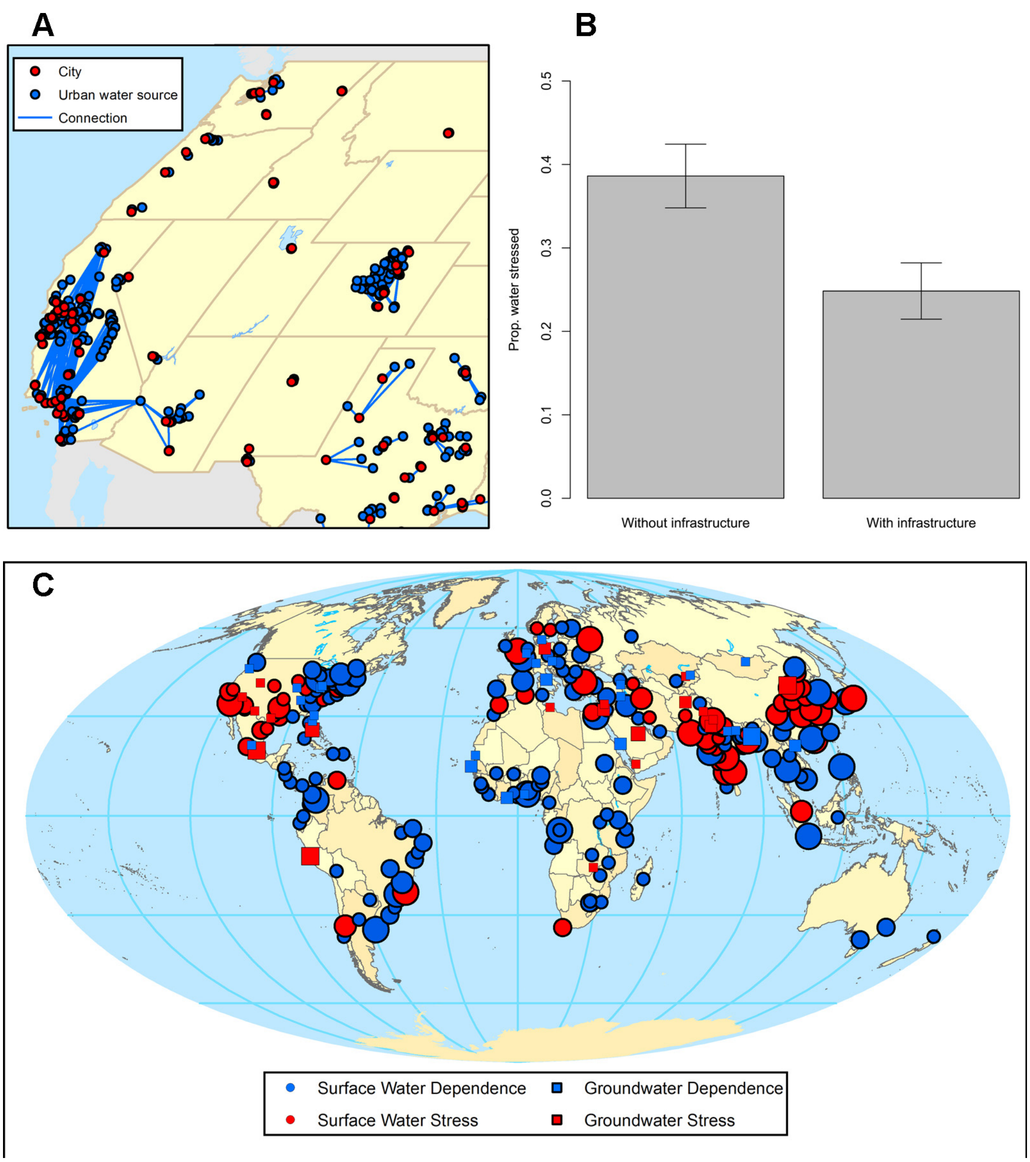

Fig. 1. Hydraulic infrastructure enables many cities to escape water stress. (A) Graph of hydraulic connections between urban water sources and the cities they serve for one example region, the southwestern United States. (B) Proportion of cities in water stress if one assumes water withdrawal occurs where a city is located, which is often assumed in global hydrologic models, versus if one uses the locations of the actual water sources. (C) Surface water and groundwater dependence and stress for large cities in our global survey, after accounting for their hydraulic infrastructure. The size of each point symbol is proportionate to the population of the urban agglomeration.

(WaterGAP estimate: 40 ± 4%). While urban infrastructure may help many cities escape water stress, some cities still are taking water from rivers that are being ecologically impacted by excessive water withdrawals.

Our analysis found evidence for both geographical and financial limitations affecting patterns of urban water scarcity.

We assessed the geographical limitation by quantifying how far cities would have to go to reach potential unstressed sources (Fig. 3A). Around 80% of all large cities would have to travel less than 22 km to reach a potential unstressed water source of 1000 million liters per day (MLD), a common volume for a water system for cities of several million people. However, 10% of cities would have to travel more than 48 km, and 5% of cities would have to travel more than 94 km. Accessing a large potential unstressed water source of 10,000 MLD, roughly the size of the water systems of world's largest cities, requires traveling even farther: 10% of cities would have to travel more than 265 km, and 5% of cities would have to travel more than 385 km. For cities that face a geographical limitation and are far from potential unstressed sources, escaping water stress requires constructing infrastructure to transport water a long distance.

We quantified financial limitation by assessing per-capita income in cities relative to the distance water is transported (Fig. 3B). Cities with fewer financial resources must survive on closer water sources. Cities with low per-capita income (<\$1035/person, in US2005\$, corrected for purchasing power parity) extend on average 26 ± 6 km, while cities with high per-capita income (>\$12,616/person) have sources that are on average 57 ± 7 km away ($F = 3.55$, $P = 0.02$). Middle income cities are intermediate between low and high-income cities.

Looking forward to the next few decades, it seems likely there will be a significant expansion in urban water infrastructure. Much of this new infrastructure will have to be built by cities with relatively few financial resources. The annual population growth rate of a city is negatively correlated with per-capita income ($F = 359.7$, $R^2 = 0.36$, $P < 0.001$), which suggests that the fastest growing cities of the next few decades will have substantially fewer financial resources than the average city

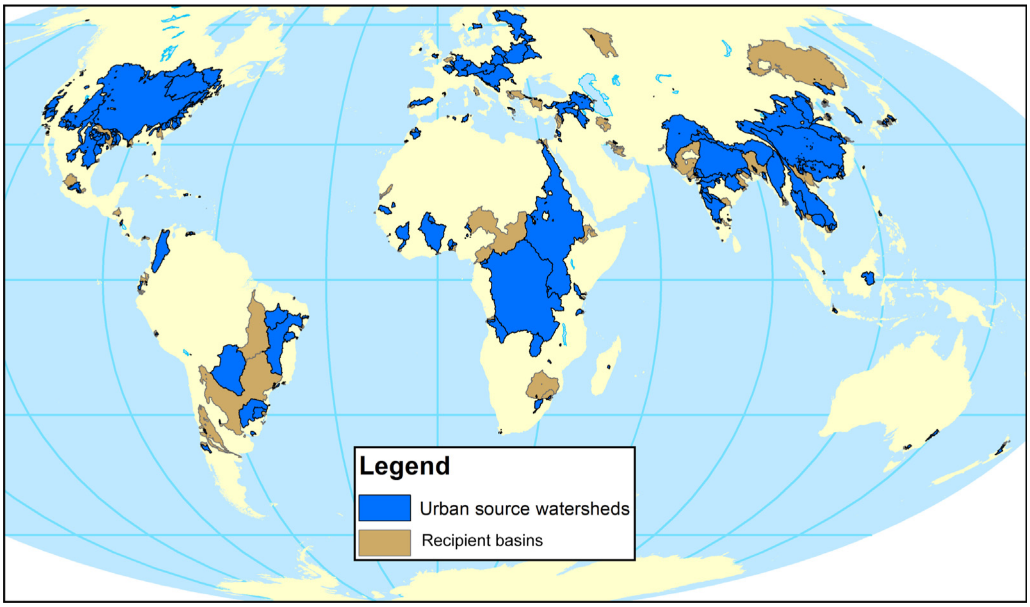

Fig. 2. The upstream contributing area of cities in our survey. Urban source watersheds are shown in blue. Also shown in brown are basins that have a gain in water balance due to municipal transfers by cities in our survey, but do not serve as supply watersheds. These recipient basins receive water from cross-basin municipal transfers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(Fig. 4). Urbanization is part of the economic development of most countries, so it is not surprising that developing countries, where per-capita income is less, also have faster population growth in cities (Montgomery et al., 2003). In the long-term, urbanization is expected to increase the financial resources available to cities in the developing world (Montgomery et al., 2003). In the short-term, however, cities with relatively few financial resources have to find alternative ways to quickly build water systems to accommodate some of the world's fastest urban growth.

Some of the fastest growing cities of the 21st century are in areas with a geographical limitation in water availability. A spatial assessment of all large cities with severe geographical limitation, defined as cities that have to go out farther than 100 km to reach an unstressed water source of 1000 MLD, shows that the majority (68%) of large cities with severe geographical limitation are located in low to middle income countries, most notably focused in China, Central Asia, and Mexico. These cities face a double-bind: they

Table 1
Largest cross-basin transfers by large cities in our sample. A cross-basin transfer is defined as the surface withdrawal of water from a drainage basin that does not contain any part of the urban agglomeration.

Urban agglomeration	Country	Population (2010)	Cross-basin transfer (million liters per day)
Los Angeles	United States	13,223,000	8895
Boston	United States	4,772,000	3307
Mumbai	India	19,422,000	3220
Karachi	Pakistan	13,500,000	2529
Hong Kong	China	7,053,000	2447
Alexandria	Egypt	4,400,000	2300
Tianjin	China	8,535,000	2179
Tokyo	Japan	36,933,000	2170
San Francisco	United States	3,681,000	2014
San Diego	United States	3,120,000	1442
Ahmadabad	India	6,210,000	1363
New York	United States	20,104,000	1348
Tel Aviv	Israel	3,319,000	1225
Pretoria	South Africa	1,468,000	1217
Sydney	Australia	4,479,000	1210
Chennai	India	8,523,000	1130
Algers	Algeria	2,851,000	1070
Aleppo	Syria	3,068,000	1062
Athens	Greece	3,382,000	1036
Cape Town	South Africa	3,492,000	994

Table 2
Largest cities under water stress in our sample. The water sources are shown, as well as if they are stressed in our analysis (WBM = Water Balance Model shows stress, WG = WaterGAP model shows stress).

Urban agglomeration	Country	Population (2010)	Sources
Tokyo	Japan	36,933,000	Surface (WG)
Delhi	India	21,935,000	Surface (WBM, WG), Ground
Mexico City	Mexico	20,142,000	Ground (stress), Surface
Shanghai	China	19,554,000	Surface (WBM, WG), Ground
Beijing	China	15,000,000	Ground (stress), Surface
Kolkata	India	14,283,000	Surface (WBM, WG), Ground
Karachi	Pakistan	13,500,000	Surface (WBM, WG), Ground
Los Angeles	United States	13,223,000	Surface (WBM, WG), Ground
Rio de Janeiro	Brazil	11,867,000	Surface (WG)
Moscow	Russia	11,472,000	Surface (WBM, WG), Ground
Istanbul	Turkey	10,953,000	Surface (WG), Ground
Shenzhen	China	10,222,000	Surface (WG)
Chongqing	China	9,732,000	Surface (WBM), Ground
Lima	Peru	8,950,000	Surface (WG), Ground (stress)
London	United Kingdom	8,923,000	Surface (WBM, WG), Ground
Wuhan	China	8,904,000	Surface (WBM, WG)
Tianjin	China	8,535,000	Surface (WBM, WG), Ground
Chennai	India	8,523,000	Surface (WG), Ground
Bangalore	India	8,275,000	Surface (WG), Ground
Hyderabad	India	7,578,000	Surface (WBM, WG), Ground

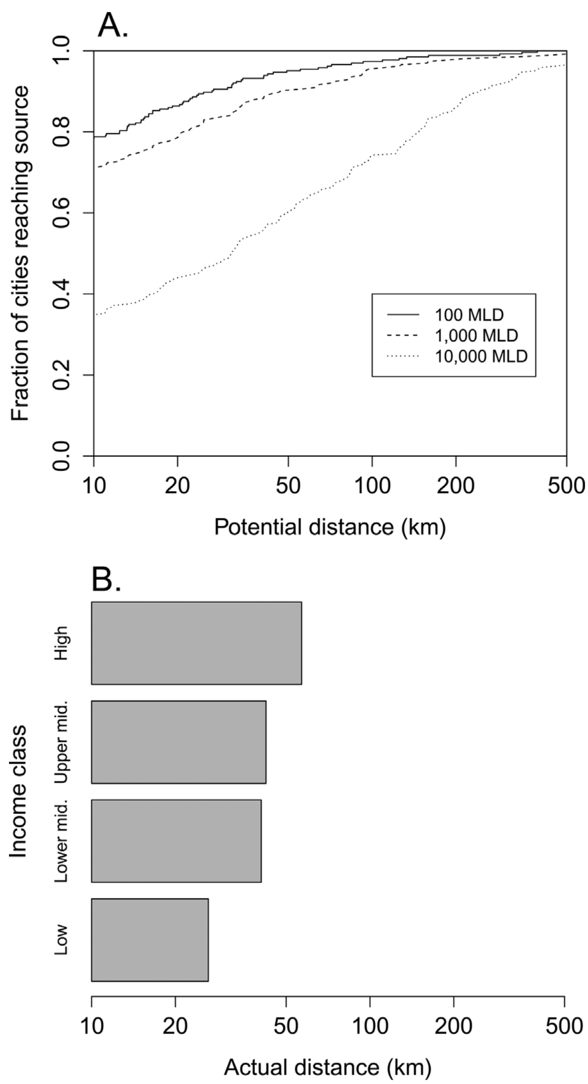

Fig. 3. Limitations cities face in obtaining water. (A) Geographical limitation in obtaining water. Due to local geography, cities have to go different distances to obtain adequate water from an unstressed water source. At a given potential distance traveled, only some fraction of cities will have reached a potential unstressed water source of adequate volume. Three volume categories were considered: 100 million liters per day (MLD), 1000 MLD, and 10,000 MLD. (B) Financial limitation on the distance water is actually transported. Income categories are based on subnational per-capita income data from the G-Econ database (Nordhaus et al., 2012), using the income categories of the World Bank. On average, cities with more income have infrastructure that transports water farther than low income cities, which appear financially limited. Note that the *x*-axis is the same as in (A), so the two panels can be directly compared.

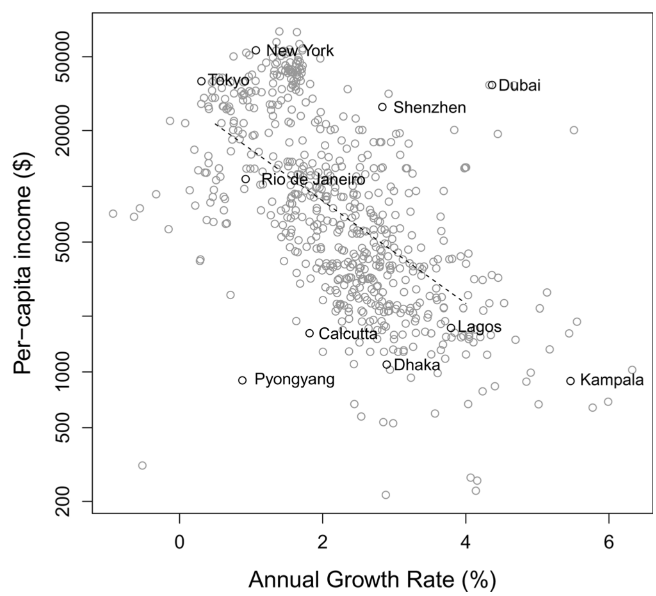

Fig. 4. Faster growing cities have less financial resources. The annual population growth rate of large cities globally is negatively correlated with the per-capita income ($R^2 = 0.36, P < 0.001$), and hence tend to go out less far for their water source (Figure 2B). For illustrative purposes, a few large cities are labeled on the graph.

have to overcome a geographic limitation with relatively few financial resources. Collectively, these fast-growing, geographically limited cities contain $330 billion in economic activity, close to 2% of the total economic activity in large cities. In the coming decades, these cities will likely account for an even larger proportion of global economic activity, since the countries they are located in are predicted to grow faster economically than the global average (OECD, 2012; World Bank, 2011).

4. Discussion

Our analysis shows that accounting for urban water infrastructure is essential for accurately estimating the urban population in water stress. Previous global analyses of water stress have likely overstated urban water stress because they have not accounted for this infrastructure. We also show that urban water infrastructure is quite large in scope, drawing water from almost half of the global land surface and transporting water and transporting water a cumulative distance of 27,000 ± 3800 km. As global urbanization progresses, and another 2 billion people move into cities over the next few decades (UNPD, 2011), the scope of urban water infrastructure seems likely to increase even farther.

We find evidence that both geographical and financial limitations are important for determining patterns of urban water scarcity. The solutions to urban water scarcity vary depending on which limitation a city faces.

In regions with a geographical limitation in water availability, such as the western United States and northern China, increased coordination among cities throughout the region may be required to provide adequate water supplies to all cities. Essentially, this is a collective action problem, which requires a regional water management solution. When a geographical region of limited water availability is within one country, the national government often designs the system, as in the complex set of transfers from the Colorado River in the United States and the south-to-north transfer system in China. For water scarce regions, making more efficient use of available water, by decreasing leakage from urban water systems, increasing the use of recycled water, and increasing the efficiency of agricultural irrigation, may become increasingly important. Coastal cities in water-scarce regions may also turn to desalination, although it remains a relatively expensive solution.

In financially limited cities, increased investment will be needed to create adequate urban water supply infrastructure. In many cities in middle income countries, economic growth will be more than adequate to finance bonds for new urban water infrastructure. However, for the poorest cities, which are also generally the fastest growing, international aid and investment may be required to maintain adequate urban water supply. Cities in the least developed countries are generally in this category, such as Kampala (Uganda) and Dhaka (Bangladesh). Our results suggest that cities in a double bind, both geographically and financially limited (e.g., Sana'a in Yemen), will be in greatest need of aid.

Authors' contribution

R.I.M. conceived of the analysis, led the assembly of the City Water Map, and led the analysis. K.W. assembled the data for the City Water Map, J.P. contributed a large dataset for the United States, and T.B. helped with data processing. M.F. and C.S. conducted the analysis for WaterGap, P.G. for WBM, and T.G. for the Groundwater Footprint. S.E. conducted the statistical analysis. D.B. and M.M. contributed demographic information. B.L. and G.G. conducted hydrologic routing calculations. All authors co-wrote the paper.

Conflict of interest

The authors declare no competing financial interests.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2014.04.022.

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