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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